WATER CONSUMPTION OF SOUTH AFRICAN VINEYARDS : A MODELLING APPROACH BASED ON THE QUANTIFIED COMBINED EFFECTS OF SELECTED VITICULTURAL, SOIL AND METEOROLOGICAL PARAMETERS

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DECLARATION

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and I have not previously in its entirety or in part submitted it at any university for a degree.

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OPSOMMING

Normaalweg word slegs een of twee stelle gewasfaktore in kombinasie met 'n verwysingwaterverbuik (ET_o) vir die beraming van gewas waterverbruik (ET) van wingerde gebruik. As gevolg van variasie tussen wingerde beperk hierdie gewasfaktore die akkuraatheid waarmee produsente besproeiing kan bestuur om produksie en gehalte te optimiseer. Die doel van hierdie studie was om 'n waterverbruikmodel, wat die variasie tussen wingerde in ag neem, te ontwikkel.

Die hittepuls tegniek is gekalibreer om sapvloei oor kort periodes in wingerdstamme te meet. 'n Kalibrasiekurwe vir sapvloei teenoor tyd is ontwikkel. Om vir variasie van sapvloei in xileem voorsiening te maak, is vier sensors per stam gebruik. Sapvloei is in geselekteerde wingerde onder verskillende toestande gemeet. Daaglikse sapvloei per stok het toegeneem met blaaroppervlak. Uurlikse sapvloei het nie reglynig met straling toegeneem nie, wat daarop gedui het dat maksimum huidmondjie-opening net 'n vaste hoeveelheid transpirasie toegelaat het. In sommige gevalle het sapvloei gedurende die dag tydelik afgeneem wat op 'n waterbesparingsmeganisme as gevolg van huidmondjie-sluiting onder toestande van hoë ligintensiteit gedui het. In vergelyking met droëlandtoestande, het besproeiing slegs aanvanklik hoë sapvloeipieke geïnduseer. Dit het impliseer dat, benewens verhoogde transpirasie, turgiditeit in selle ook herstel is. In vergelyking met loweroppervlak-oriëntasie en meteorologiese toestande, het oeslading en besproeiing beperkte effekte op daaglikse sapvloei gehad. Tagtig persent van variasie in sapvloei kan op grond van blaaroppervlak en ET_o voorspel word. As gevolg van verskille in die hoeveelheid blare aan straling blootgestel, was die voorspelling meer akkuraat wanneer tussen horisontale en vertikale lowers onderskei is. Aangesien toename in beskaduwing met 'n toename in lowerdigtheid, asook kultivareienskappe en waterspanning, nie in ag geneem is nie, word hierdie modelle as 'n eerste benadering beskou.

'n Li-Cor LAI-2000 Plant Canopy Analyzer (PCA) is in geselekteerde wingerde gekalibreer om blaaroppervlakindeks (BOI_{pca}) te meet. Alhoewel die PCA werklike blaaroppervlakindeks (BOI) onderskat het, is die nou korrelasie tussen BOI_{pca} en BOI gebruik om blaaroppervlakontwikkeling te meet. Blaaroppervlakontwikkeling is in agt wingerde, wat ten opsigte van kultivar, plantafstand en prieelstelsel verskil het, in vyf wingerdbougebiede gemeet. Seisoenale verandering in blaaroppervlak kon met derde orde polinomiese vergelykings, met dag van groeiseisoen as enigste veranderlike, voorspel word. Afsonderlike potensiële groeikurwes is vir die Winterreën en Somerreën gebiede ontwikkel. Die gebruik van lootmassa om maksimum blaaroppervlak te voorspel, was minder akkuraat as wanneer die vars blaarmassa gebruik is. Horisontale priële het meer blare per eenheid lootmassa as vertikale priële geproduseer. Water wat daagliks in bogrondse dele van die wingerdstok gestoor word, het slegs breukdele van 'n millimeter beloop en kon dus in die voorspelling van waterverbruik geïgnoreer word.

Verdamping vanaf die grondoppervlak (E_s) is met mini-lisimeters in wingerde gemeet om die Boesten & Stroosnijder model te evalueer en aan te pas. Onder nat grondtoestande was daar 'n neiging tot hoër

E_s in die middelste gedeelte van die werksry. Verdamping vanaf onbewerkte grond sonder 'n deklaag is met aanvaarbare akkuraatheid deur die model voorspel. Die model moes egter aangepas word om interaksie tussen die lower en grond in ag te neem. Daar was 'n neiging tot hoër E_s onder horisontale priële as by vertikale priële gedurende fase twee van verdamping. Verdamping het ook tussen die ses grondtipes wat in hierdie studie gebruik is, verskil. 'n Strooideklaag het E_s betekenisvol onder relatiewe nat toestande beperk. Vir die meeste gronde het die deklaag na tien dae geen verskil in vergelyking met grond sonder 'n deklaag gehad nie. Daar was 'n reglynige verband tussen kumulatiewe E_s en ET_o vasgestel. Kumulatiewe E_s was gemiddeld ongeveer 30 % van kumulatiewe ET_o.

Die transpirasie en oppervlakverdamping modelle is gekombineer om as basis vir 'n voorlopige voorspellingsmodel vir evapotranspirasie te dien. Gesimuleerde ET is teenoor werklike ET, soos gemeet in agt wingerde onder verkillende toestande, vergelyk. Hierdie wingerde het 'n reeks veranderlikes soos besproeiingstelsel, grondtipe, grondwateronttrekkingspeile, prieelstelsel en groeikrag aangespreek. Slegs eenvoudige parameters soos lootmassa, plantafstand, loweroppervlak-orientasie, verwysingswater-verbruik en 'n konstante waarde wat die verdampingsverliese vanaf 'n spesifieke grondtipe bepaal, is as invoere gebruik. Gesimuleerde ET het bevredigend met werklike ET vergelyk, en dus die akkuraatheid van die model bevestig.

ABSTRACT

Generally only one or two sets of crop coefficients are used in combination with a reference crop evapotranspiration (ET_o) to estimate evapotranspiration (ET) of vineyards. Due to the variation among vineyards, these crop coefficients restrict the accuracy of estimating ET required by producers to manage irrigation to optimize yield as well as grape and wine quality. The aim of this study was to develop a water consumption model that could account for variation among vineyards.

The heat pulse velocity technique was calibrated for measuring sap flow over short periods of time in grapevine trunks. A calibration curve of sap flux against time was developed. At least four probes were used per trunk to account for sap flow variability in xylem. Hourly sap flow was measured in selected vineyards under different conditions. Diurnal sap flow increased with leaf area per vine. Hourly sap flow did not increase linearly with net radiation, which suggested that maximum stomatal opening only allowed a fixed amount of transpiration. In some cases, sap flow also showed a temporary decrease during the day, which indicated a possible water saving mechanism resulting from stomatal closure at high light intensities. In comparison to non-irrigated grapevines, irrigation induced initial high sap flow peaks which indicated that, in addition to increased transpiration, turgidity was also regained. Eighty percent of variation in total diurnal sap flow could be explained by means of linear regression when only leaf area and ET_o were considered. Due to differences in amount of leaves exposed to direct net radiation, variation in sap flow was predicted more accurately by linear models for horizontal and vertical canopies, respectively. Since increase in shading with increase in leaf layers, cultivar characteristics and water stress effects were not accounted for, these models are regarded as a first approach.

A Li-Cor LAI-2000 Plant Canopy Analyzer (PCA) was calibrated to measure leaf area index (LAI_{pca}) in selected vineyards. Although the PCA underestimated actual leaf area index (LAI), the close correlation between LAI_{pca} and actual LAI was used to measure leaf area development. Leaf area development was measured in eight vineyards varying in cultivar, vine spacing and trellising system in five grape growing regions. Seasonal leaf area development could be predicted by means of a third order polynomial equation using day of season as the independent variable. Potential growth curves were developed for the Summer and Winter Rainfall regions, respectively. Using cane mass to predict maximum leaf area was not as accurate as using leaf fresh mass. Horizontal canopies tended to produce more leaf area per unit cane mass in comparison to vertical canopies. Water stored daily in the above-ground parts of the grapevine only amounted to fractions of a millimetre, suggesting that water used for maintaining cell turgidity and physiological processes other than transpiration could be ignored in modelling water consumption.

Evaporation losses from the soil surface (E_s) were measured under grapevine canopies by means of mini-lysimeters to evaluate and adapt the Boesten & Stroosnijder evaporation model. Under wet soil conditions, E_s tended to be higher in the middle section of the work row. Evaporation from unmulched,

untilled soil was estimated with acceptable accuracy by the Boesten & Stroosnijder model. Since this model was initially developed for bare, fallow soils, some adaptations were necessary to account for canopy shading effects. During stage two evaporation, E_s tended to be higher under a horizontal trellis in comparison to a vertical trellis. Furthermore, E_s differed between the six soil types used in this study. Mulching reduced E_s significantly under relatively wet soil conditions. For most soils there were no difference between E_s for unmulched and mulched soils ten days after irrigation. Cumulative E_s from mulched soil correlated linearly with cumulative ET_o and generally amounted to approximately 30 % of cumulative ET_o.

A combination of the transpiration and evaporation models were used as basis to design a draft water consumption model to estimate evapotranspiration of individual vineyards. Simulated ET was compared to actual ET measured for eight vineyards under different conditions. These vineyards represented various sets of variables which included irrigation system, soil type, soil water depletion level, trellising system and vigour. Only inputs such as cane mass, vine spacing, canopy surface orientation, reference crop evapotranspiration data as well as a constant value, which determines the amount of evaporation from a specific soil type, were required for the estimation of ET. The accuracy of the model was verified satisfactorily by simulation of measured ET.

WATER IN ONS LEWENS

Die woordeboek beskryf water as kleurloos, smaakloos en reukloos - met as belangrikste eienskap sy vermoë om ander stowwe op te los. Ons in Suid-Afrika sien water nie so nie. Vir ons is water 'n basiese mensereg; water is die oorsprong van alle dinge - die gewer van lewe. Die digter Mazisi Kunene het gesê dat alle volke van die aarde uit water gebore is.

Daar is water binne-in ons; laat daar water by ons wees. Water rus nooit. Wanneer dit daarbo vloei, veroorsaak dit reën en dou. Wanneer dit daaronder vloei, vorm dit strome en riviere. Indien 'n baan daarvoor gemaak word, vloei dit daarlangs. En ons wil daardie baan maak. Ons wil hê die water van hierdie land moet in 'n netwerk invloei - na elke individu toe - en sê: Hier die water, vir jou. Neem dit; koester dit as bevestiging van jou menswaardigheid; voed jou menslikheid daarmee. Met water sal ons die verlede wegwas; ons sal van nou af altyd deur die seën van water gebind word.

Water het baie vorms en baie stemme. Sonder om geëer te word, terwyl hy sy seisoene en buie behou, sy ritmes en syferstraaltjies, is water daar in die kleuterslaapkamer; is water daar in die appelkoosboom wat sy skaduwee oor die agterplaas gooi; is water in die reuk van druiwe op 'n herfsbord, is water daar in die klein wit intimiteit van onderklere was. Water - wat sedert die begin van die tyd bymekaar en opgegaar is in graniet - en rotslae, in die omhelsing van damme, die klowe van riviere- sal eendag onaangekondig, beskeie, maklik en eenvoudig deurvloei na elke Suid-Afrikaner wat 'n kraan oopdraai. Dit is my droom.

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CHAPTER 1

INTRODUCTION

1.1 THE NEED FOR QUANTIFYING WATER CONSUMPTION OF SOUTH AFRICAN VINEYARDS

Grapevines, like most agricultural crops, depend on adequate water for normal functioning and economically viable production. Water requirement is defined as the total quantity of water, regardless of its source, required by crops for their normal growth under field conditions. It may include water applied in irrigation, precipitation and soil water available to the crops (Van der Watt & Van Rooyen, 1990). Evapotranspiration is defined as the combined loss of water from a given area and during a specific period of time, by evaporation from the soil surface and by transpiration from plants (Van der Watt & Van Rooyen, 1990).

During 1997 total area of grapevine plantings in South Africa was estimated at 108 880 hectares. This figure included wine, table and raisin grapes. In most viticultural regions of South Africa, precipitation is not sufficient to meet the water requirements of grapevines during the growing season. Consequently, irrigation is essential to maintain production and quality of 86 885 hectares, *i.e.* 80 % of South African vineyards (Table 1.1). Depending on the climatic region, estimated water requirements of these vineyards can vary between 286 mm and 860 mm (Van Zyl, 1981). Limited surface as well as subsurface water resources, however, necessitate accurate irrigation management.

In addition to wasting water, over-irrigation may induce waterlogged soil conditions, leach nutrients from the root zone and cause chemical degradation of natural water resources. An evaluation of irrigation system design and management in the Breede River Valley revealed that, although irrigation system design was of a high standard, large potential drainage losses may result from ineffective irrigation scheduling (Murray Biesenbach & Badenhorst Inc, 1993). Furthermore, unnecessary energy inputs will contribute to high production costs. Injudicious irrigation can cause excessive vegetative growth which in turn, will cause shading of buds to such an extent that grapevine fertility is reduced (Carbonneau & Casteran, 1979). Excessive growth may also reduce fruit quality (Williams, Dokoozlian & Wample, 1994) as well as wine quality (Archer & Strauss,1989b). Removal of excessive growth to improve the microclimate in grapevine canopies will increase production costs. Effective application of chemicals for disease control in grapevine canopies will also be hampered by too vigorous vegetative growth (Smart, Dick, Gravett & Fisher, 1990).

In contrast to over-irrigation, severe water deficits induced by insufficient irrigation may result in poor vegetative growth, economically unviable production and unacceptable grape quality

(Williams *et al*, 1994). Water stress significantly reduces bud fertility of Cabernet Sauvignon at 80 % depletion of plant available water in comparison to 40 % depletion (Buttrose, 1974). Berry size, which is an important quality parameter for export table grapes, can be significantly reduced by insufficient water supply (Myburgh, 1996).

The aim of irrigation scheduling is to ensure that grapevines have sufficient water available between consecutive irrigations. To achieve this, soil water should not be depleted below critical levels during various phenological phases. The cell division period during berry development can be regarded as the most sensitive to insufficient water supply (Van Zyl, 1984). However, 50 % depletion of plant available water (PAW), which will allow sufficient cell division, is generally recommended during all phenological phases. The effect of soil water depletion level on berry size and quality parameters of table grapes, cv. Barlinka, on a sandy soil in the Hex River Valley is shown in Table 1.2 (Myburgh, 1996). It is clear that wet (10 % PAW depletion) soil conditions favoured berry size, but reduced grape colour and taste. On the other hand, dry (60 % PAW depletion) soil conditions resulted in poor berry size and eating quality. Optimum balance between production and quality was obtained with irrigation at 40 % depletion of PAW. Considering the sandy nature of the soil, these findings support the fact that 50 % can generally be regarded as an acceptable available soil water depletion level.

1.2 IRRIGATION SCHEDULING APPROACHES

1.2.1 Direct methods

Soil water depletion can be monitored or measured either directly or indirectly. The direct approach entails measuring soil water content (SWC). This can be achieved gravimetrically by means of soil samples or by using electronic devices associated with more advanced techniques such as neutron scattering and time domain reflectometry. Regular monitoring of SWC gravimetrically on a commercial scale is time consuming and thus not practical. However, the gravimetric method is regarded as the most accurate and is, as such, used for calibration and evaluation of more advanced methods.

Using more advanced techniques requires high capital investment, calibration curves for different soil types and layers, as well as skilled labour. Tensiometry, which indicates the matrix potential of soil, can also be used to determine the SWC. However, soil water characteristic curves must be determined to convert matrix potential accurately to soil water content. Compared to the gravimetric method, these techniques are rapid and allow regular monitoring of SWC. Problems are, however, encountered around placement of access tubes, probes and tensiometers, particularly where soils are unevenly or partially wetted with micro irrigation systems such as drippers.

1.2.2 Indirect methods

By means of the indirect approach, evapotranspiration of vineyards can be related to a reference measure of water consumption or evapotranspiration using the following equation (Doorenbos & Pruitt, 1977):

$$ET = K_c \times ET_o \tag{1.1}$$

where ET is the crop evapotranspiration over a given period and ET_o is the reference crop evapotranspiration which is defined as the rate of evapotranspiration from an extensive surface of 80 mm to 150 mm tall, green cover of uniform height actively growing, completely shading the ground and not short of water (Doorenbos & Pruitt, 1977). The constant of proportionality, K_c, is generally referred to as the crop coefficient. More recently, the grass reference evapotranspiration (ET_o) was redefined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0,12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0,23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height actively growing, completely shading the ground and with adequate water (Allen *et al*, 1994). Since it is impractical to measure ET_o as defined above, meteorological parameters have been used for indirect assessment of evapotranspiration. Various equations have been designed in this regard. Evapotranspiration has been related to monthly percentage of annual total hours of sunshine and monthly mean temperature (Blaney & Criddle, 1950). Jensen & Haise (1963) proposed a method to estimate ET from solar radiation. Linacre (1977) only used air temperature to estimate evaporation. However, a more realistic approach seems to be to calculate ET_o from a combination of meteorological parameters (Penman, 1948; Monteith, 1985). Currently the modified Penman-Monteith equation, which uses parameters such as radiation, humidity, air temperature and wind speed, is regarded as the most suitable for calculation of ET_o (De Jager & Van Zyl, 1989). Furthermore, electronic technology development has brought about automatic recording weather stations capable of measuring the meteorological parameters required for real time calculation of ET_o by means of the modified Penman-Monteith equation.

According to Doorenbos & Kassam (1979), reference crop evapotranspiration (ET_o) can also be obtained from :

$$ET_o = K_p \times E_p \tag{1.2}$$

where E_p is American Class-A pan evaporation in mm d^{-1} and respresents the mean daily value of the period considered. The constant of proportionality, K_p, is a set of empirically derived pan coefficients which take into account climate and pan environment (Doorenbos & Pruitt, 1977).

Equations 1.1 and 1.2 can be combined to calculate ET as follows:

$$ET = K_c \times K_p \times E_p \qquad (1.3)$$

Furthermore, K_c and K_p can be combined in a single coefficient, K_{cp}, as follows:

$$K_{cp} = K_c \times K_p \qquad (1.4)$$

For the purpose of this study, K_{cp} will be referred to as the pan crop coefficient.

Evaporation from a pan, as measured by means of the American Class-A pan (E_p), was, and still is, widely used in South Africa as a measure of reference evapotranspiration. Consequently, pan crop coefficients (K_{cp}) for estimating water consumption of South African vineyards have been developed primarily for the Class-A pan (Van Rooyen, 1980; Van Zyl & Weber, 1981; Van Zyl, 1984; Fourie, 1989; Myburgh, 1992). Other evaporation pans, such as the Scheepers-pan, were also designed for use in irrigation scheduling (Scheepers, 1975). However, these pans are not commonly used due to the fact that the American Class A-pan is used as standard by the South African Weather Bureau. Pan crop coefficients are only valid for the specific pan and locality used for determining reference crop evapotranspiration. This is also true for specific methods of calculating ET_o from climatic data, *e.g.* by means of the modified Penman-Monteith equation or the Blaney-Criddle equation as reported by Van Zyl & Weber (1981).

Pan crop coefficients are not constant over the growing season and generally increase as leaf area increases. Variations in climatic conditions affect transpiration demand, evaporation from the soil surface as well as the reference evaporation. Consequently, seasonal climatic variations will also contribute to variations in pan crop coefficients.

1.3 FACTORS INFLUENCING WATER CONSUMPTION AND PAN CROP COEFFICIENTS

Research has shown that soil water depletion increases as root density and thus leaf area of Pinot noir grapevines increases with plant density (Archer & Strauss, 1989a). Seasonal soil water depletion by Sultanina on a 300 mm wide T-trellis amounted to 715 mm in comparison to 762 mm depletion by larger grapevines on a 900 mm wide trellis (Prior & Grieve, 1986). However, higher water consumption of bushvines with a leaf area of 10,2 m^2 vine $^{-1}$ compared to grapevines on a slanting trellis with a leaf area of 13,7 m^2 vine^{-1} revealed that vineyard water consumption is not solely a function of leaf area (Van Zyl & Van Huyssteen, 1980). This suggested that canopy effects such as leaf and soil surface shading as well as air flow beneath the foliage, which are induced by different trellis configurations, also influence water consumption. The same study showed that the windbreak effect of a vertical lengthened Perold system reduces water consumption compared to a horizontal slanting trellis.

Irrigation increased transpiration rates of Pinot noir grapevines significantly in comparison to dryland conditions (Myburgh, Van Zyl & Conradie, 1996). Transpiration rates of irrigated grapevines, however, did not increase with an increase in canopy size as quantified by pruning mass. Allowing the soil to dry out to different plant available water (PAW) depletion levels can also influence grapevine water requirements substantially (Van Zyl, 1984; Fourie, 1989). This variation is not only caused by a decrease in transpiration as plant water stress increases, but more frequent wetting of the surface due to shorter irrigation cycles to maintain higher soil water availability can also increase evaporation losses (Hillel, 1980).

Method of cultivation also has an affect on soil water status and consequently, on grapevine water use (Van Huyssteen & Weber, 1980). In this regard, tillage practices such as mulching can reduce evaporation losses compared to unmulched soil (Van Huyssteen, Van Zyl & Koen, 1984; Van Zyl & Myburgh, 1997). A cover crop still growing after bud break increased water consumption of a Colombar vineyard in the Little Karoo compared to unmulched soil (Van Huyssteen, Van Zyl & Koen, 1984). This effect, however, was only significant up to flowering. Loosening the topsoil by tillage three days after an irrigation, increased evaporation losses over the following eighteen day period (Van Zyl & Myburgh, 1997).

Where grapevines received only two or three irrigations during the season, pan crop coefficients were generally lower (Van Zyl & Weber, 1981) in comparison to situations where climatic conditions required more frequent irrigation (Van Zyl, 1984). Pan crop coefficients for table grapes were generally higher compared to wine grapes under comparable climatic conditions (Van Rooyen, 1980; Fourie, 1989). This suggests that the purpose for which grapevines are grown also affects pan crop coefficients. Furthermore, it was established that the development stage of young vines as well as vigour induced by available soil depth had an appreciable effect on water consumption of Pinot noir grapevines (Myburgh, Van Zyl & Conradie, 1996). Water consumption increased from 263 mm in the first year to 614 mm in the third year. Williams (1993) also reported an increase in the annual water consumption from 356 mm to approximately 800 mm as young Sultanina grapevines developed to the full-bearing stage.

Type of irrigation system can also influence irrigation requirements when the soil is only partially wetted by means of drippers, compared to full surface wetting in the case of micro-sprinklers or flood irrigation (Van Zyl, 1984). Furrow irrigation reduced water consumption of Colombar by

53,7 % compared to full surface flood irrigation (Van Zyl & Van Huyssteen, 1988). A 15,5 % reduction in water consumption of Sultanina was obtained by means of drip irrigation in comparison to furrow irrigation (Araujo, Williams & Matthews, 1995). In addition to partial wetting, which reduces evaporation losses from the surface, the efficiency of application of the irrigation system also affects irrigation water requirements. The estimated distribution of irrigation systems commonly used in the South African grape growing regions is presented in Table 1.3. Efficiencies of application are generally accepted as 90 % for drippers, 80 % for micro-sprinklers, 70 % for overhead sprinklers and 60 % for flood irrigation. A situation where ten combinations of irrigation systems and soil water depletion levels were applied in a field trial near Robertson, resulted in the same number of pan crop coefficient sets (Van Zyl, 1984). Although some systems are predominantly used in some regions, *e.g.* 70 % flood irrigation in the Lower Orange River Valley, the total vineyard areas irrigated by the four commonly used systems are more or less the same (Table 1.4).

Pan crop coefficients published by Green (1985) are generally accepted to estimate vineyard water requirements for irrigation scheduling as well as for irrigation system design purposes. These pan crop coefficients primarily distinguish between table and wine grapes. For the latter case, the coefficients are further sub-divided to distinguish between sub-intensive and intensive irrigation for untrellised and trellised vineyards, respectively. Class-A pan crop coefficients determined by previous research are summarised in Table 1.5. The variation in pan crop coefficients demonstrates how combinations of viticultural practices and locality can influence water requirements. Hence, in order to estimate water consumption of vineyards more accurately, the effect of the variables, as discussed above, should be considered.

Transpiration through leaves or canopies and evaporation from the soil surface are the two main processes involved in water losses in vineyards (Smart & Coombe, 1983). The dynamics of these processes are controlled by environmental conditions, soil surface conditions as well as viticultural aspects. In order to account for the effect of variables on water consumption, their effects on the processes responsible for water losses should be considered. However, in most previous irrigation research, evapotranspiraton of grapevines was regarded as a single process. Until recently, little effort has been made to study the individual water consumption roles of evaporation and transpiration. Some of the first studies in this regard have shown that transpiration was only 33 % of evapotranspiration of a Chardonnay vineyard in Texas (Lascano, Baumhardt & Lipe, 1992). These results were quite contradictory to the general assumption that evapotranspiration is dominated by water extraction by the grapevine.

1.4 MODELLING WATER CONSUMPTION

Various water consumption models have been developed to estimate evapotranspiration of agricultural crops under South African conditions (Boedt & Laker, 1985; De Jager, Van Zyl, Kelbe & Singels, 1987; Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, 1988). Since these models were developed specifically for annual crops such as maize and wheat, they are not suitable to accommodate the large variation in viticultural practices and conditions. However, at this stage there is no crop-specific water consumption model capable of accounting for the large variations between vineyards.

Considering the variations encountered among vineyards, there is a need to develop a specific evapotranspiration model for grapevines. The high cost of research to determine crop coefficients (K_c or K_{cp}), as well as the impracticalities of determining crop coefficiënts for every vineyard, serve as further motivation to develop an evapotranspiration model. Developing a water consumption model would involve the separation of evaporation losses from the soil and transpiration by grapevines.

A water consumption model proposed by Jensen, Wright & Pratt (1971) may serve as an example of a model for use under viticultural conditions. This model was derived from the basic model presented in equation 1.1 by expanding the crop coefficient (K_c), as follows :

$$K_c = (K_{cb} \times K_{cs}) + K_{so} \tag{1.5}$$

where, K_{cb} is the basal crop coefficient for conditions where soil water depletion is not critical and water loss is by transpiration. In fact, K_{cb} relates transpiration losses to reference crop evapotranspiration. K_{cs} is the plant water stress coefficient that accounts for transpiration reduction at critical levels of soil water depletion and K_{so} is the coefficient that accounts for evaporation losses from the soil surface. The plant water stress coefficient, K_{cs}, can be calculated as follows (Jensen *et al*, 1971) :

$$K_{cs} = \ln(A_w + 1) \ / \ \ln(101) \tag{1.6}$$

where A_w is the percentage plant available soil water. At field capacity A_w equals 100 % and at permanent wilting point A_w equals 0 %. The coefficient for evaporation from the soil surface is calculated as follows :

$$K_{so} = A_f \ (1 - K_{cb}) \ (1/N)^t \tag{1.7}$$

where, A_f is the fraction of the surface that is wetted, K_{cb} is the basal crop coefficient, N is soil texture constant which varies from 1,0 for clay to 3,5 for coarse sand and t is the number of days after irrigation or rain. As described above, the model distinguishes between evaporation and transpiration by considering the following variable parameters :

1. Natural increase in leaf area over the season as represented by the basal crop coefficient (K_{cb}).
2. Decrease in transpiration induced by soil water depletion (K_{cs}).
3. Partial wetting of the soil surface or the type of irrigation system (A_f).
4. Soil texture (N).

To use this type of model for grapevines, the following parameters should be determined to obtain a more crop-specific model :

1. The leaf area development of grapevines over the growing season, as well as transpiration as a function of leaf area to determine K_{cb}.
2. The effect of cultivar characteristics, *e.g.* stomatal density, on transpiration.
3. The validity of applying the plant stress coefficient (K_{cs}) to grapevines under normal soil water content ranges.
4. Soil texture constants (N) for vineyard soils in South Africa.
5. Evaporation from the soil surface under grapevine canopies.
6. Soil tillage effects on evaporation from the soil surface.

Furthermore, it is important that the final model should be applicable to all viticultural situations. This can only be achieved by determining water consumption in a wide range of vineyards under diverse conditions. The validation has to address :

1. Young grapevines.
2. Various canopy sizes and leaf surface orientation.
3. Vine spacing.
4. Different climatic regions.
5. Wine, table and raisin grapes.
6. Various irrigation systems.
7. Different soil textures.
8. Various plant available water depletion levels.
9. Different tillage methods.

A water consumption model based on the indirect approach should be compatible with reference evaporation determined by means of the American Class-A pan as well as the modified Penman-Monteith equation. In future, more institutions and agricultural organizations will resort to automatic weather stations and consequently, the modified Penman-Monteith equation will probably be used on a larger scale than the American Class-A pan.

If the model estimates water consumption satisfactorily, a computer program should be developed to facilitate the calculation of seasonal water consumption from long term average reference evaporation, for use in planning of water storage capacities and in irrigation system design. Furthermore, the computer program must also enable producers to predict real time water consumption on a daily base.

Accurate water consumption modelling by means of a user friendly computer program will not only be of value for irrigation scheduling to improve irrigation water use efficiency, but will also enable producers to manipulate soil water content to optimize yield as well as grape and wine quality, which are the ultimate objectives of grape production in South Africa.

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TABLE 1.1

Estimated area under grapevines in South Africa during 1997 (Anonymous, 1997).

Region	Total (ha)	Area (ha)		
		Dryland	Irrigated	
		Wine grapes	Wine/dried grapes	Table grapes*
Lower Orange River Valley	17 107		12 692	4 415
Olifants River Valley	8 280		7 909	371
Malmesbury	12 582	8 518	4 064	
Little Karoo	3 577		3 178	399
Paarl	18 912	5 029	11 586	2 297
Robertson	11 125		11 125	
Stellenbosch	15 499	8 448	7 051	
Worcester	15 925		15 499	426
Hex River Valley	4 154			4 154
Piketberg	1 100			1 100
Transvaal	399			399
Other	220			220
Total	**108 880**	**21 995**	**73 104**	**13 781**

* J.T. Loubser, ARC Nietvoorbij Centre for Vine and Wine, Personal communication, 1998.

TABLE 1.2

Average berry mass, taste and colour of table grapes (cv. Barlinka) as measured over three seasons (1993 - 1995) in an irrigation trial on a sandy soil in the Hex River Valley (Myburgh, 1996).

Plant available water depletion (%)	Berry mass (g)	Taste*	Colour*
60	4,88 b**	3,67 b	4,32 b
40	6,08 a	5,41 a	5,38 a
10	6,45 a	3,59 b	3,46 b

* Location values calculated using the PC-Plum statistical program for conversion of non-parametric data. These values are dimensionless.

** Values followed by the same letter do not differ significantly ($p \leq 0,05$).

TABLE 1.3

Estimated distribution of irrigation systems in viticultural regions of South Africa (Anonymous, 1997).

Region	Irrigation systems used (%)			
	Flood	Overhead sprinklers	Micro-sprinklers	Drippers
Orange River Valley	70		15	15
Olifants River Valley	40		10	50
Malmesbury		60	25	15
Little Karoo	15	25	30	30
Paarl		60	25	15
Robertson	15	25	20	40
Stellenbosch		60	25	15
Worcester	10	20	40	30
Hex River Valley*			70	30
Piketberg**		10	50	40
Transvaal***			95	5

* C. De Jager, Department of Agriculture Western Cape, Personal communication, 1998.

** J.T. Loubser, ARC Nietvoorbij Centre for Vine and Wine, Personal communication, 1998.

*** J.H. Avenant, ARC Nietvoorbij Centre for Vine and Wine, Personal communication, 1998.

TABEL 1.4

Vineyard areas irrigated by means of the most commonly used irrigation systems in South Africa during 1997 as estimated from data presented in Tables 1.1 and 1.3.

Irrigation system	Irrigated area (ha)	% of total
Flood	19 085	22,0
Overhead-sprinklers	21 969	25,3
Micro-sprinklers	23 259	26,7
Drippers	22 572	26,0
Total	86 885	

TABLE 1.5

American Class-A pan crop coefficients (K_{cp}) as established for wine and table grapes at various localities under diverse viticultural conditions as well as the general pan crop coefficients used for irrigation system design and planning.

Locality	Only variable under otherwise comparable conditions	Pan crop coefficient					
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Stellenbosch (Van Rooyen, 1980)	Table grapes	0,15	0,20	0,30	0,42	0,35	0,25
(Van Zyl & Weber, 1981)	Wine grapes	0,36	0,32	0,27	0,22	0,25	0,25
Robertson (Van Zyl, 1984)	Micro-sprinklers	0,31	0,47	0,50	0,48	0,48	0,46
	Drippers	0,13	0,36	0,32	0,29	0,34	0,32
	Overhead sprinklers	0,30	0,44	0,50	0,47	0,53	0,52
	Flood irrigation	0,28	0,36	0,38	0,52	0,52	0,45
Robertson (Van Zyl, 1984)	Irrigation at 50 % PAW* depletion	0,29	0,46	0,48	0,51	0,49	0,53
	Irrigation at 70 % PAW* depletion	0,31	0,47	0,50	0,48	0,48	0,46
	Irrigation at 90 % PAW* depletion	0,27	0,43	0,45	0,49	0,46	0,43
De Doorns (Fourie, 1989)	Irrigation at field capacity	0,28	0,41	0,66	0,77	0,79	0,50
	Irrigation at 15 % PAW* depletion	0,13	0,27	0,39	0,47	0,62	0,57
	Irrigation at 50 % PAW* depletion	0,22	0,34	0,36	0,50	0,60	0,63
	Irrigation at 85 % PAW* depletion	-	0,22	0,19	0,33	0,36	0,43
Stellenbosch (Myburgh, 1992)	Strong vigour (1200 mm depth)	0,21	0,42	0,62	0,54	0,45	0,35
	Moderate vigour (800 mm depth)	0,16	0,29	0,48	0,41	0,40	0,27
	Poor vigour (400 mm depth)	0,13	0,29	0,37	0,27	0,27	0,16
Stellenbosch** (Myburgh, Van Zyl & Conradie, 1996)	First leaf grapevines	0,18	0,13	0,17	0,23	0,22	0,24
	Second leaf grapevines	0,18	0,18	0,24	0,25	0,32	0,46
	Third leaf grapevines	0,34	0,22	0,39	0,43	0,41	0,38
General (Green, 1985)	Wine grapes, sub-intensive	0,15	0,25	0,25	0,25	0,25	0,20
	Wine grapes, intensive	0,23	0,38	0,38	0,38	0,38	0,30
	Table grapes	0,15	0,20	0,30	0,40	0,35	0,25

* Plant available water.

** Calculated from published water consumption figures.

CHAPTER 2

CALIBRATING A HEAT PULSE VELOCITY TECHNIQUE TO ESTIMATE SAP FLOW IN GRAPEVINE TRUNKS

2.1 INTRODUCTION

To quantify the contribution of transpiration towards total evapotranspiration, water loss through the entire canopy must be known. Various techniques have been developed to measure transpiration rate and to establish the temporal variation thereof. In this regard, porometers have been widely used to measure transpiration in terms of stomatal conductance or stomatal resistance in grapevines. Since the application of porometers is limited to measuring single leaves, it is not suitable for estimation of whole plant transpiration rates. Hence, porometers were generally applied in comparative studies to assess treatment effects on transpiration rates (Düring & Loveys, 1982; Van Zyl, 1987). In an attempt to estimate stem flow in honey mesquite (*Prosopis glandulosa*) by means of scaling porometer measurements, it was found that the accuracy of sap flow estimations declined at higher transpiration rates (Ansley, Dugas, Heuer & Trevino, 1994).

Whole plant transpiration estimates are generally obtained by means of the stem heat balance or the heat pulse velocity techniques. The stem heat balance approach involves determining heat transported by sap mass flow by drawing up a heat balance for a stem segment supplied with a known amount of heat (Baker & Van Bavel, 1987). Stem sap flow is estimated from the heat transported by sap mass flow. The stem heat balance technique has been used in various studies to estimate sap flow in crape myrtle (Zajicek & Heilman, 1991), *Eucalyptus grandis* (Savage, Graham & Lightbody, 1993; Lightbody, Savage & Graham, 1994), *Guiera Senegalensis* and sunflower (Grime, Morison & Simmonds, 1995). Using a commercially available stem heat balance system, estimations of daily sap flow in young Chardonnay grapevines were within 5 % to 10 % of gravimetrically obtained values (Lascano, Baumhardt & Lipe, 1992). However, when using this technique on apple trees, calculated sap flow rates showed errors of more than 20 % (Weibel & De Vos, 1994). This was caused by improper gauge contact, lags in response time and heat damage to bark tissues. Accuracy was improved to acceptable standards when the gauge was modified to obtain optimum contact and by operating the system by means of continuously controlled power supply.

Schmid (1997) used a method based on heat conductance to measure sap flow in grapevines. This system consisted of an upstream and a downstream heat sensor installed approximately 10 mm to 15 mm apart in the xylem tissue. Heat is constantly supplied to the upstream sensor. The temperature difference between the sensors is a function of the sap flow rate. When sap flow is zero, heat builds up around the upstream sensor and the temperature difference is at a maximum value. As soon as sap flow occurs, heat around the upstream sensor is conducted by convection and the temperature difference drops. Hence, the higher the sap flow rate the lower the temperature difference. The difference between daily sap flow measurements using this technique was generally less than 10 % when compared to gravimetrically determined water loss.

In a review of transpiration estimation techniques, measuring heat pulse velocities (HPV) in stems to determine sap flow was regarded as a "well developed method to determine transpiration" (Ziemer, 1979). The heat pulse velocity technique has been shown to be suitable for estimating sap flow in kiwifruit (*Actinidia chinensis*) (Edwards & Warwick, 1984); kiwifruit (*Actinidia Leliciosa*) and apple (*Malus sylvestris*) (Green & Clothier, 1988); kiwifruit roots and stems (Green & Clothier, 1995) as well as grapevines (*Vitis vinifera*) (Eastham & Gray, 1998).

In principle, the time is taken for a heat pulse to propagate in the xylem tissue of a stem or trunk. From this time measurement the speed of moving sap can be determined. Generally sap flow is obtained by numerical solution of the heat transport equation for implanted sensors (Swanson & Whitfield, 1981). However, to achieve accurate estimations, parameters such as wood density, wound size caused by probes as well as probe separation should be considered. Long term sap flow measurements in *Eucalyptus grandis* were obtained by means of the heat pulse velocity technique when proper calibration procedures to account for wood density, wound size and probe separation were followed (Olbrich, 1991). These parameters can only be assessed by means of destructive methods. Hence, application of the HPV technique is limited when destruction of experimental plants is not permissible. Since wound size effects only increase with time, it was suggested that HPV measurements could be carried out over short periods with freshly installed probes to avoid wound size determination by destructive methods (Swanson & Whitfield, 1981).

The aim of this study was to calibrate the HPV technique for measuring sap flow in grapevine trunks over short periods after probe installation.

2.2 MATERIALS AND METHODS

2.2.1 Experimental grapevines

Calibrations of the HPV technique were performed on four different grapevines. The first calibration was done during October 1994 in a sixteen year old own rooted Sultanina vineyard at the Upington Experimental Station of the Department of Agriculture Northern Cape in the lower Orange River Valley. Grapevines were planted 3,0 m x 1,5 m and trained onto a 2,4 m slanting trellis (Zeeman, 1981). A second calibration was done early in December 1994 in a sixteen year old Barlinka/Ramsey table grape vineyard at the Hex Valley Experimental Station of the ARC-

Infruitec/Nietvoorbij near De Doorns. These grapevines were planted 3,0 m x 1,8 m and were also trained onto a 2,4 m slanting trellis.

At the end of December 1994, a third calibration was performed using a three year old 99 Richter rootstock obtained from the nursery at the Nietvoorbij Centre for Vine and Wine. This grapevine was planted in a 8 dm^3 plastic container filled with a sand and tree bark growth medium. Shoots were trained onto a 1,0 m high, vertical stake inserted in the container.

During late January 1995, a fourth calibration was performed in a nine year old Pinot noir/99 Richter vineyard at the Nietvoorbij Centre for Vine and Wine of the ARC-Infruitec/Nietvoorbij at Stellenbosch. Grapevines were spaced 3,0 m x 1,5 m and trained onto a vertical lengthened Perold system (Booysen, Steenkamp & Archer, 1992). In each vineyard a representative grapevine, not showing any signs of water or nutrient deficiencies, was selected. These grapevines were bordered by at least five vines in the row and at least two rows from the edges of the respective vineyards.

2.2.2 **Direct water uptake**

Water uptake of the Sultanina grapevine was first determined by means of the cut-tree method described by Olbrich (1991). However, due to rapid wilting despite cleaning the cut using a sharp blade after cutting, the following excavation procedure was employed. A circular trench, 600 mm deep and 300 mm wide, was excavated *ca* 600 mm from the grapevine trunk. Soil between the remaining roots was removed rapidly taking care not to damage too many roots. Roots penetrating deeper than 600 mm were cut off. After shaking off the remaining soil, the roots were placed in a 20 dm^3 plastic bucket filled with water. The grapevine, with its canopy still intact, suspended from the trellising system. At this stage two 800 mm long steel posts were driven into the intact soil outside the pit. A 3,0 m long wooden beam was fixed securely to the posts in such a way that it crossed close to the grapevine trunk at the original soil surface level. The lower 150 mm of the trunk was wrapped in two layers of 0,8 mm thick plastic for protection, and secured to the beam to stabilize the grapevine.

After removing roots thicker than 10 mm in diameter under water, remaining roots were tightly bound together in a bundle of *ca* 250 mm in diameter. A smaller 400 mm diameter plastic container filled with clean water was placed around the root-bundle. At the same time an electronic balance was placed underneath the bucket. Care was taken to avoid roots touching the sides of the bucket. To minimize evaporation losses, the bucket was covered by means of a cardboard cover consisting of two halves with an opening in the middle which fitted closely around the trunk. The cover was removed during weighing.

Direct water uptake was recorded hourly during the day and every two hours from dusk to dawn for at least 48 hours or until grapevines showed signs of permanent wilting. The plant material, *i.e.* roots and lower part of trunk, suspended in the water contributed to the total mass recorded by means of the balance. This caused mass losses to be unequal to the actual volume of water taken up by the roots. To calculate the actual volume of water taken up, the electronic balance was calibrated as follows. After a sap flow calibration run was terminated, water was added in 50 ml volumes by means of a pipette to a total of 250 ml. Mass increase for each 50 ml addition was recorded. Depending on the amount of water lost from the bucket, this was repeated at up to three different water levels. The linear regression of volume on mass was used to convert mass differences to volumetric water uptake. The foregoing procedures were employed where calibrations were performed on the three excavated mature grapevines.

Water uptake by the potted 99 Richter rootstock was recorded directly by means of an electronic balance. In this case, the recorded water uptake included transpiration losses as well as water lost or gained by the plant tissue. To avoid water evaporation, the growth medium surface was covered completely by means of a candle wax layer. Four 2,0 mm diameter holes were drilled in the wax layer to allow watering when necessary. Water uptake was recorded hourly from 06:00 until 20:00 for a period of 72 hours.

Assuming that trunks were cylindrical and that homogeneous flow occurred over the entire cross section, sap flux was calculated as follows :

$$v = V/At \tag{2.1}$$

where v is sap flux (ml cm^{-2} h^{-1}), V is direct water uptake (ml) calculated from the mass loss by assuming the density of the water to be one, A is cross sectional area of the trunk (cm^2) and t is time (hour).

2.2.3 Heat pulse velocity

After removing dead bark, a 20 mm thick metal jig was used to drill three 1,8 mm diameter holes parallel to each other in the sapwood of the trunk. To prevent the jig from shifting during drilling, it was secured tightly to the trunk by means of an improvised clamp (Fig. 2.1). An adjustable stop was fitted to the drill bit to ensure that holes were only drilled to the desired depths. A line source heater and two thermistor probes, which can be regarded as a sensing unit, were installed radially in the trunk as shown in Figure 2.2. Probes were installed between internodes at four positions around the trunk at various heights in the lower 400 mm section. Where possible, probes were installed at four depths to account for concentric variations in sap flow. Probe depths and trunk diameters of the experimental grapevines are presented in Table 2.1. Probe depth was always increased from the highest to the lowest position.

Heat pulse generation and temperature measurements were obtained by means of a specially designed recorder (Micro Innovations, Pretoria). Heat pulses, which lasted 1,0 second, were applied every 15 minutes and the time taken for thermistor temperatures to return to the initial balance point before heat was applied, was recorded. Readings were averaged to obtain hourly values which corresponded to the time intervals of the direct water uptake as determined by means of weighing.

Heat pulse velocity (u) in mm s^{-1} was calculated using the following formula (Swanson & Whitfield, 1981) :

$$u = (X_u + X_d)/2t \tag{2.2}$$

where X_u and X_d are distances (mm) from the upstream and downstream thermistors to the line heater, and t is the time (s) taken for the thermistors to return to the initial temperature balance point which was automatically set before the heater was pulsed. Heat pulse velocity was converted to sap flux using the following formula :

$$v = \varrho_b (m_c + 0{,}33)\, u \tag{2.3}$$

where v is sap flux (ml cm^{-2} s^{-1}), ϱ_b is wood density (Mg m^{-3}), m_c is the moisture fraction and 0,33 is the specific heat of dry wood (Swanson & Whitfield, 1981). Sap flux was converted to sap flow per grapevine using :

$$Q = 3600\, vA \tag{2.4}$$

where Q is sap flow (ml h^{-1} $vine^{-1}$) and A is the cross sectional area of the trunk (cm^2). Trunk diameter and circumference were measured at the positions where probes were installed. A was calculated as:

$$A = (C / 2\pi)^2\, \pi \tag{2.5}$$

where C is mean trunk circumference (mm). The value of π was taken as 3,14159.

2.2.4 Plant parameters

Leaf water potential (LWP) was measured by means of the pressure chamber technique (Scholander, Hammel, Bradstreet & Hemmingsen, 1965). Mature leaves, fully exposed to the sun were sampled from the "calibration" grapevine as well as two surrounding undisturbed grapevines. LWP was determined at 15:00 on the day that the calibration for Sultanina was terminated at Upington. In the case of the Barlinka grapevine, LWP was measured at 06:00, 15:00 and 18:00 during the second day of the calibration experiment. No leaf water potential measurements were made in the case of the Pinot noir grapevine or the potted 99 Richter root stock.

To determine wood density, samples were taken from trunks when sap flow measurements were terminated. After fresh mass was obtained, samples were covered by means of a candle wax layer and volumes determined by submerging in water. Wood density was obtained by dividing the fresh mass by the difference in volume before and after submerging.

The moisture fraction was measured in separate samples taken from each grapevine trunk. The samples were first weighed fresh and subsequently dried at 80 °C until constant weight was obtained. The moisture fraction (g g^{-1}) was calculated using the following formula (Olbrich, 1991):

$$m_c = (\text{fresh mass} - \text{dry mass})/\text{dry mass} \tag{2.6}$$

2.3 RESULTS AND DISCUSSION

2.3.1 Direct water uptake

Volumetric water additions corresponded linearly to mass changes recorded by means of the electronic balance for a Sultanina grapevine subjected to the modified cut-tree method. However, volume increases were not equal to changes in mass. Equations used to convert mass changes to direct water uptake are presented in Table 2.2. By ignoring these conversions, direct water uptake errors would have ranged from an underestimation of *ca* 3 % to an overestimation of *ca* 14 %, as was the case for the calibration performed on the Sultanina grapevine at Upington.

Water uptake rates of excavated grapevines measured by means of the electronic balance ranged between almost zero and about 6 ml cm^{-2} h^{-1}. In the case of the potted 99 Richter grapevine, water uptake rates ranging between almost zero and *ca* 11 ml cm^{-2} h^{-1} were recorded. Tyloses, which block conducting vessels naturally, normally occurs in older wood. Xylem vessels are inactivated by tyloses when two to three years old, and are completely inactivated in six to seven years (Pratt, 1974). Hence, tyloses blockage of conducting vessels could have caused the lower sap flow rates measured in the older trunks. Disturbance of the grapevine physiology due to excavation, could also have reduced water uptake compared to the undisturbed potted grapevine.

2.3.2 Physiological response

Two days after excavation, the Sultanina grapevine at Upington showed almost no signs of wilting, which suggested that the water requirements could be met. Water requirements could have been small due to a relative small leaf area as well as cool climatic conditions prevailing at the beginning of the season (Smart & Coombe, 1983). This was supported by the fact that average LWP was - 1025 kPa and - 971 kPa for the excavated calibration vine and surrounding vines, respectively.

The Barlinka grapevine used in the De Doorns experiment showed signs of wilting during the second day. The large difference in leaf water potential at dawn (06:00) between the excavated grapevine and surrounding grapevines measured on the day after excavation, showed that water requirements could not be replenished during the previous night (Table 2.3). Water stress remained high during the day and only near dusk did the excavated grapevine regain turgidity to some extent which was reflected in the leaf water potential at 18:00. Larger leaf area and warmer conditions compared to the situation during the first calibration at Upington was probably the reason that the excavated Barlinka grapevine could not absorb sufficient water. The Pinot noir grapevine used in the Nietvoorbij experiment reacted similarly to the Barlinka grapevine. Excavation definitely had a negative effect on grapevine physiology and water uptake. This also prevented typical diurnal fluctuations in sap flow (Fig. 2.3, 2.4, 2.5 & 2.6). However, due to relative short periods over which the calibration experiments were conducted, it was assumed that physiological damage did not cause a reduction in xylem conductivity of the excavated grapevines. As expected, the potted grapevine showed no signs of wilting at any stage during the experiment.

2.3.3 Variability among sensors

Considerable inconsistency occurred among probes installed at different depths in the xylem of the Sultanina trunk (Fig. 2.3). Variation in the degree of tyloses in various sections of a single trunk could have caused the variation in sap flow. Sap flow through the outer layers of xylem is generally regarded to be higher compared to the older wood closest to the centre (Winkler, 1962). However, there was no consistency in the variation of sap flow with increasing probe depth. Sap flow tended to decrease with depth, except for the 28 mm deep sensor (Fig. 2.3). Unfortunately, recording by the outer probe (7 mm depth) was interrupted shortly after the start of the experiment. Consequently, it is not certain if sap flow rates at this depth would have remained consistently higher compared to deeper wood layers for the duration of this experiment.

In the De Doorns experiment sap flow rates in the Barlinka trunk tended to vary less among sensors (Fig. 2.4). Furthermore, no definite decrease in sap flow rate with increasing probe depth was measured for this grapevine. This suggested that the wood was reasonably homogeneous in its water translocation ability. During the calibration with Pinot noir, the highest flow rates were recorded at 10 mm depth for most of the time (Fig. 2.5). Flow rates at 12 mm, 14 mm and 16 mm depths tended to be consistently lower compared to 10 mm depth. Sap flow in younger wood (4 mm depth) of the young 99 Richter grapevine was, except for two recordings, consistently higher compared to flow at 6 mm depth (Fig. 2.6). From these results it appeared that higher sap flow rates could only be expected in outermost wood, i.e. youngest xylem, of grapevine trunks. To account for the variation either caused by tyloses or xylem age, at least four sensors at different depths should be installed if the heat pulse velocity technique is used for estimating sap flow in grapevines.

2.3.4 Calculated sap flux

Using equations 2.2 and 2.3 to calculate sap flux resulted in overestimation at low flux values and underestimation at higher flux values (Fig. 2.7). The underestimation at higher values is typical of the HPV technique (Swanson & Whitfield, 1981; Green & Clothier, 1988; Olbrich, 1991). The deviation from actual flux was relatively small, but when corrected for wound size as proposed by Swanson & Whitfield (1981), sap flux was largely overestimated (data not shown). This confirmed that wound size did not influence sap flux significantly when calculated from data obtained with freshly implanted probes. No explanation could be found for the overestimation of calculated sap flux at low actual sap flux levels.

2.3.5 Empirical calibration

Due to the abovementioned deviations of calculated sap flux, an empirical calibration approach was followed as suggested by Green & Clothier (1988) as well as Eastham & Gray (1998). For practical application, the time versus sap flux relation was inverted. This allowed direct estimation of sap flux from heat pulse propagation time recordings. Plotting actual sap flux against time taken for thermistors to reach the initial balance point, or heat pulse propagation time, revealed that this relationship showed some agreement for the three older experimental grapevines. Hence, all direct water uptake versus time data of these grapevines were pooled (Fig. 2.8). The sap flux relation versus time was curvilinear and the following exponential equation fitted this data best:

$$v = 22{,}6\, e^{(-0{,}0082t)} \qquad (R^2 = 0{,}8953) \qquad (2.7)$$

where v is sap flux (ml cm^{-2} h^{-1}) and t heat pulse propagation time (s).

The curvilinearity suggested that physical blockage of flow caused by probes (Swanson & Whitfield, 1981) probably became less significant as sap flow increased. In comparison to the older trunks, sap flux in the young 99 Richter trunk corresponded to lower time values (Fig. 2.8). Hence, sap flux (v) was related to heat pulse propagation time (t) by means of the following exponential equation:

$$v = 16{,}8\ e^{(-0{,}0085t)} \qquad (R^2 = 0{,}7621) \qquad (2.8)$$

The effect of wood density (Table 2.4) on the time versus sap flux relationship was also considered. To assess this, wood density and sap flux were used to estimate time by means of multiple regression. The following equation was obtained:

$$\ln t = -0{,}188v - 1{,}689\varrho_b + 6{,}991 \qquad (R^2 = 0{,}8846) \qquad (2.9)$$

where lnt is the natural logarithm of time, v is sap flux and ϱ_b is wood density. The correlation coefficient of the multiple linear regression was comparable to the time *versus* sap flux regression for the older grapevines. However, the standard error of estimation of sap flux for the multiple regression was 1,25 ml $cm^{-2}\ h^{-1}$ compared to 0,45 ml $cm^{-2}\ h^{-1}$ for the exponential model. This indicated that including wood density by means of multiple linear regression did not improve prediction of heat pulse progation time.

If the standard error of estimation the sap flux in grapevines with 20 cm^2 trunk diameters and a planting density of 2222 grapevines per hectare would occur over a period of 24 hours, it would mean that soil water losses due to sap flow would be under- or overestimated by 0,048 mm d^{-1}. Furthermore, if evapotranspiration is 5 mm d^{-1} the error caused by the HPV method would be ± 0,96 %.

2.4 CONCLUSIONS

This study has shown that the HPV technique could be employed to estimate sap flow in grapevine trunks. A curvilinear calibration curve of sap flux against time can be applied to estimate sap flow in grapevines. The calibration curve for nine to sixteen year old trunks, however, differed from the curve obtained for a three year old trunk. The empirical calibration models are based on the assumption that trunks are perfectly cylindrical and that concentric sap flow is homogeneous. Excavating a grapevine to measure direct water uptake increased water stress. The similarity of the calibration curve obtained by pooling the data from the older grapevines to the curve obtained for the undisturbed potted vine showed that, although water uptake rates of the excavated grapevines were lower, the actual process of water translocation in trunks was not disrupted. Using potted vines or lysimeters would allow more realistic plant physiological conditions for sap flow calibrations. However, large potted vines are not readily available. Furthermore, accurate weighing of small water losses by means of lysimetry would require expensive, sophisticated equipment.

Since wound effects, which may influence sap flow rates in long term studies (Olbrich, 1991), were ignored, these empirical calibrations would only be applicable where sap flow rates in grapevine trunks are measured within a week after probe installation. Furthermore, results suggested that wood density could be ignored, which would eliminate the need for destructive sampling of experimental grapevines. It is recommended that at least four probes are used per trunk to account for sap flow variability induced by non-homogeneous xylem vessels. If sap flow measurements were made under normal viticultural conditions, soil water losses via sap flow could be over- or underestimated by approximately 0,05 mm d^{-1}.

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TABLE 2.1

Average trunk diameter and probe depths used for the calibration of the heat pulse velocity technique on four different grapevine cultivars at three localities.

Locality	Cultivar	Trunk diameter (mm)	Probe depth (mm)			
			No. 1	No. 2	No. 3	No. 4
Upington	Sultanina	65,3	7	14	21	28
De Doorns	Barlinka	44,0	10	12	14	16
Stellenbosch	Pinot Noir	35,3	10	12	14	16
Stellenbosch	99 Richter	18,0	4	6	*	*

* Trunk length and diameter limited the installation of more than two sensors.

TABLE 2.2

Linear regression equations determined to convert water mass losses to direct volumetric water uptake during the calibration of the heat pulse velocity technique for estimating sap flow in grapevines at three localities.

Locality	Water level in bucket	Slope	Intercept	R^2
Upington	-	0,8704	0,3392	0,9997
De Doorns	High	1,0043	0,5858	0,9990
	Medium	0,9727	-0,1046	0,9999
	Low	1,0288	1,0369	0,9979
Stellenbosch	High	0,9790	-0,0686	0,9999
	Medium	0,9736	-0,1111	0,9999
	Low	0,9520	0,0321	0,9999

TABLE 2.3

Variation in leaf water potential of an excavated Barlinka grapevine, with its roots in container filled with water, compared to undisturbed control grapevines during calibration of the heat pulse velocity technique.

Treatment	Leaf water potential at different times of the day (kPa)		
	06:00	15:00	18:00
Undisturbed grapevines	-442	-1217	-652
Excavated grapevine	-1073	-1950	-782

TABLE 2.4

Wood density of grapevine trunks used in the calibration of the heat pulse velocity technique.

Locality	Cultivar	Wood density (Mg m^{-3})
Upington	Sultanina	0,52
De Doorns	Barlinka	0,54
Stellenbosch	Pinot noir	0,57
Stellenbosch	99 Richter	0,52
	Mean	**0,54**

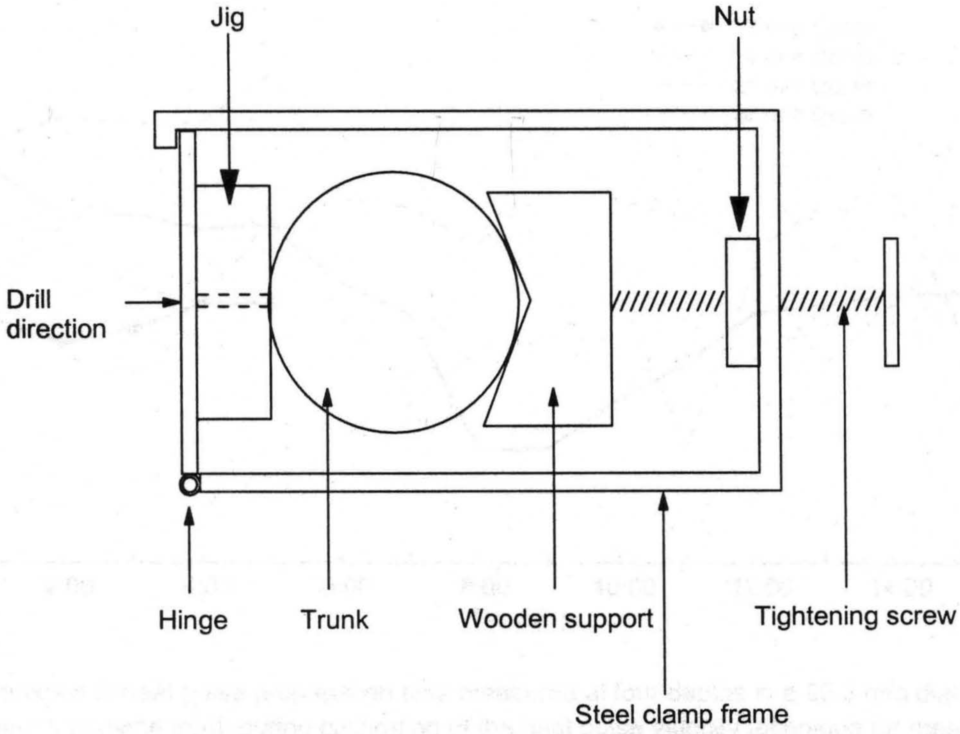

Figure 2.1. Diagram showing attachment of jig to grapevine trunk by means of a clamp, as used to drill holes for installing heat pulse velocity probes.

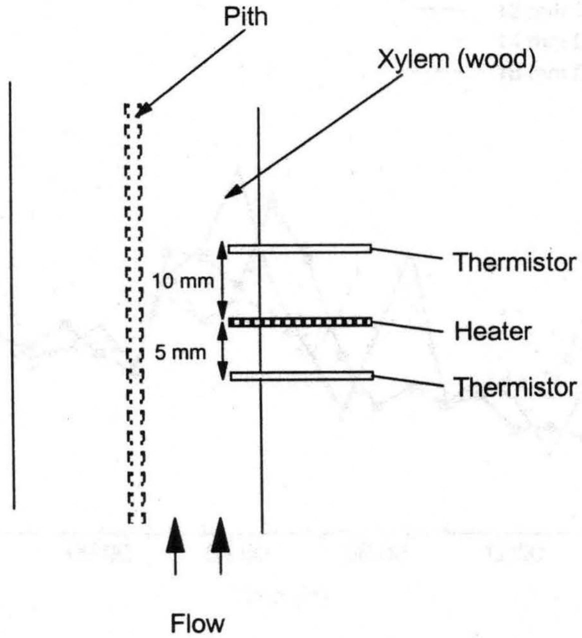

Figure 2.2. Diagram of longitudinal section through grapevine trunk showing installation of a heat pulse velocity probe.

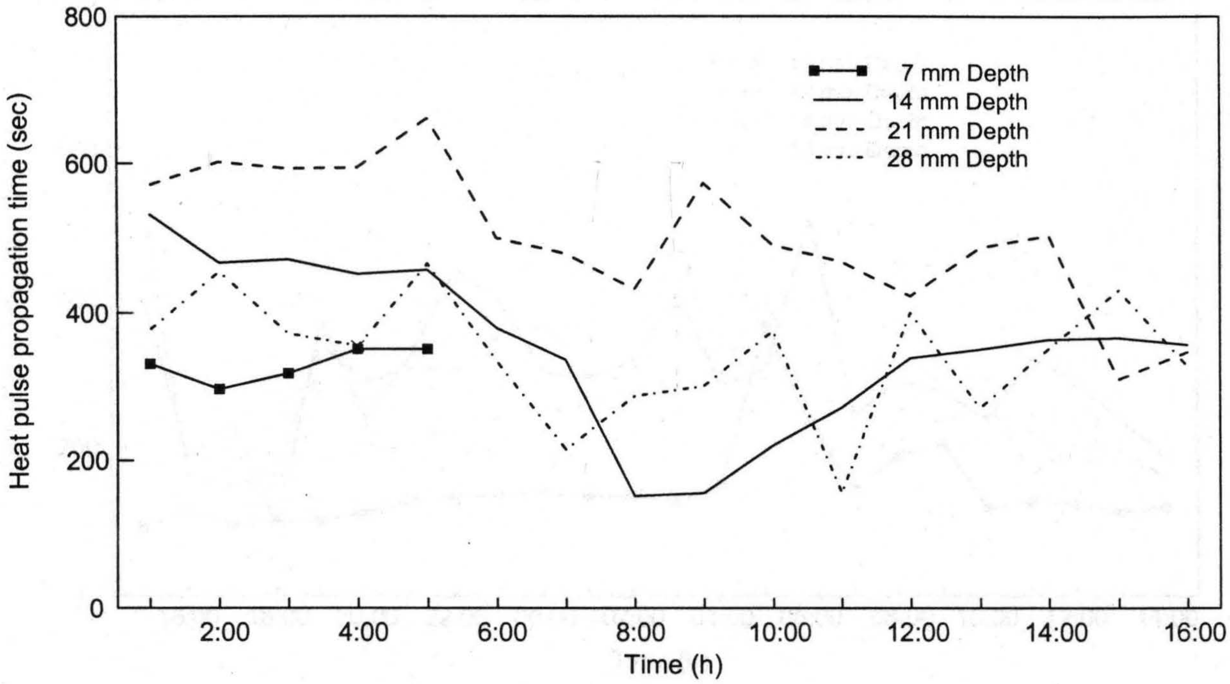

Figure 2.3. Variation in heat pulse propagation time measured at four depths in a 65,3 mm diameter Sultanina grapevine trunk during calibration of the heat pulse velocity technique for measuring sap flow in grapevines at Upington.

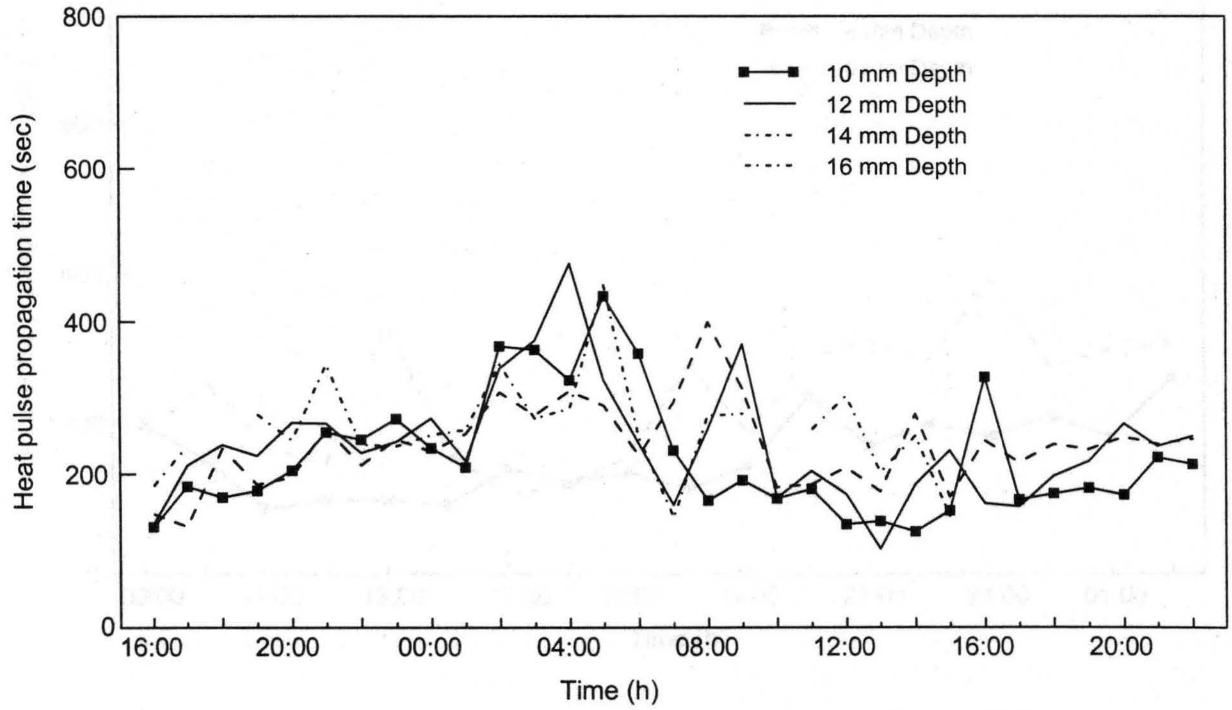

Figure 2.4. Variation in heat pulse propagation time measured at four depths in a 44,0 mm diameter Barlinka grapevine trunk during calibration of the heat pulse velocity technique for measuring sap flow in grapevines at De Doorns.

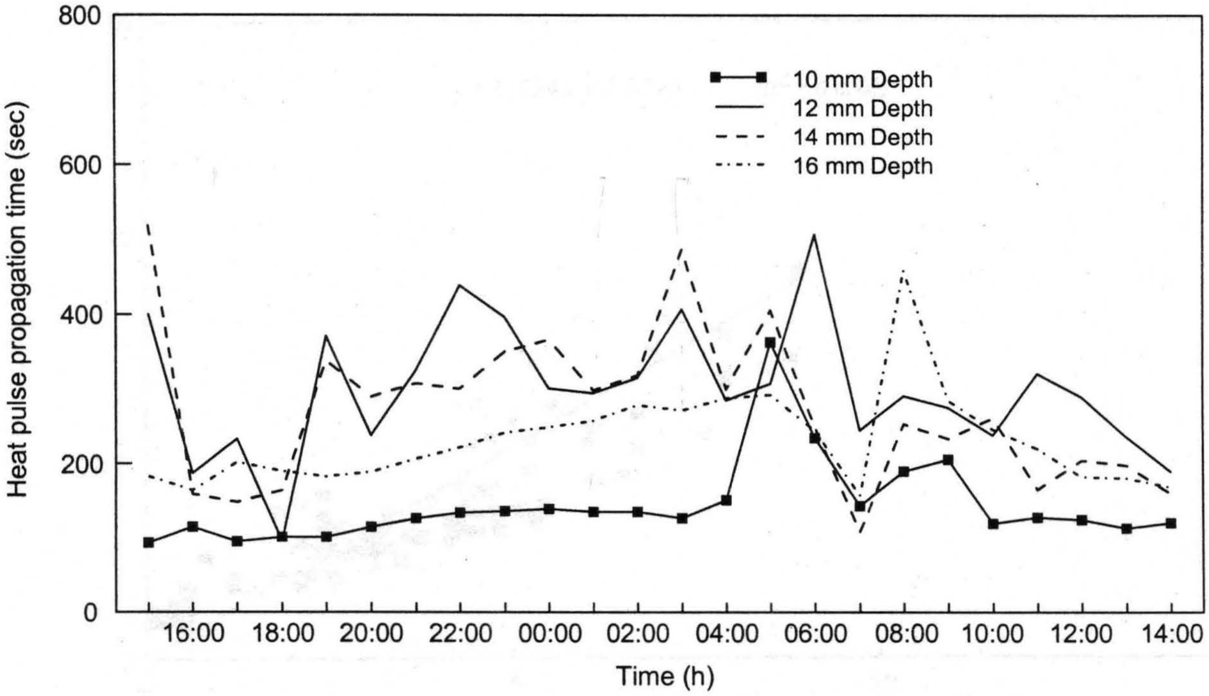

Figure 2.5. Variation in heat pulse propagation time measured at four depths in a 35,3 mm diameter Pinot noir grapevine trunk during calibration of the heat pulse velocity technique for measuring sap flow in grapevines at Stellenbosch.

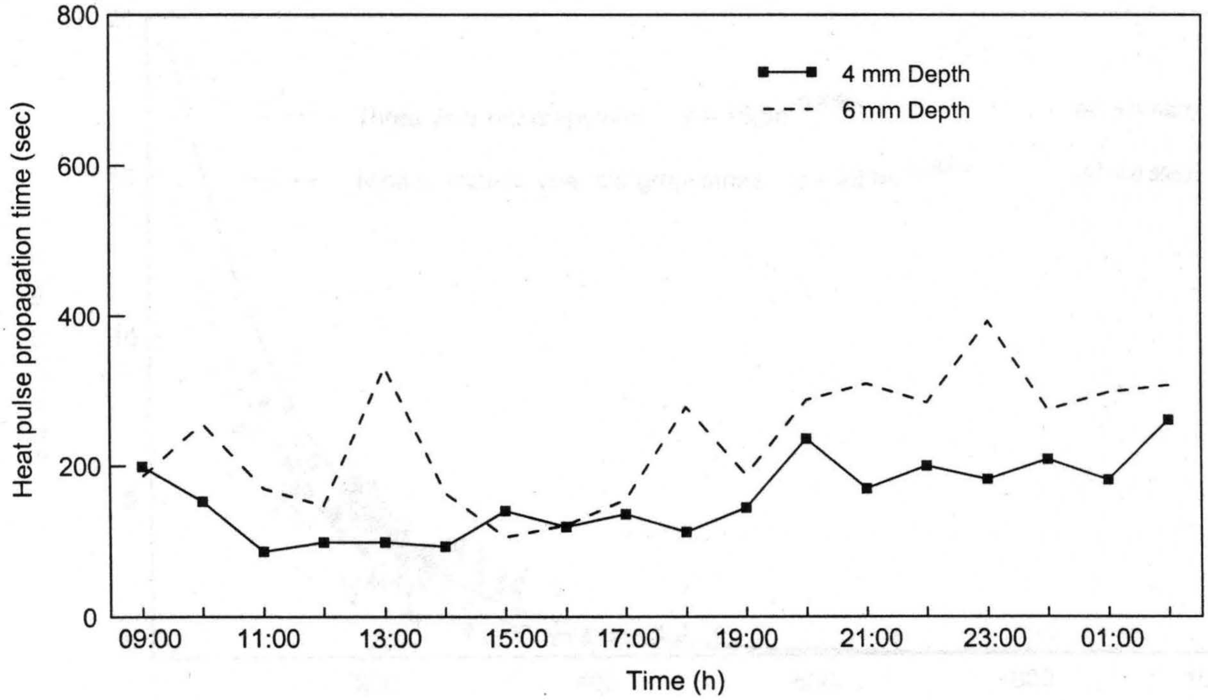

Figure 2.6. Variation in heat pulse propagation time measured at two depths in a 18,0 mm diameter potted 99 Richter rootstock trunk during calibration of the heat pulse velocity technique for measuring sap flow in grapevines at Stellenbosch.

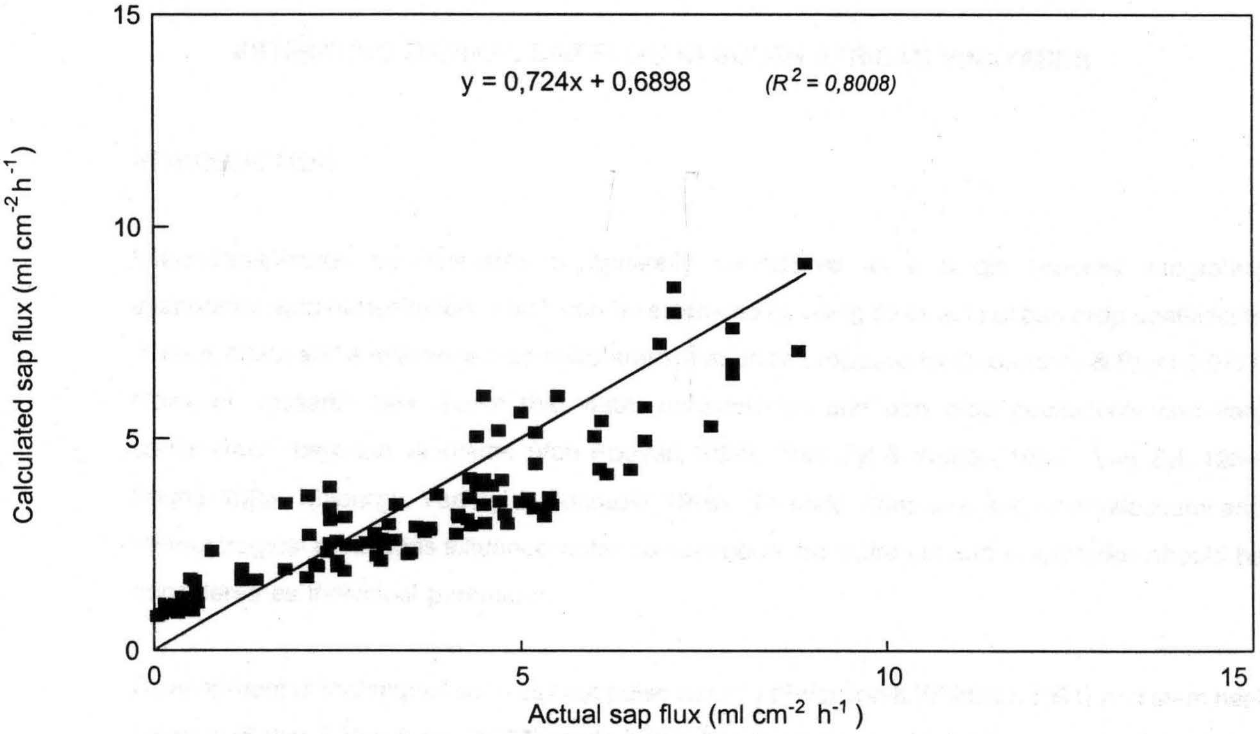

Figure 2.7. Relationship between calculated sap flux and actual sap flux as determined in four grapevine trunks.

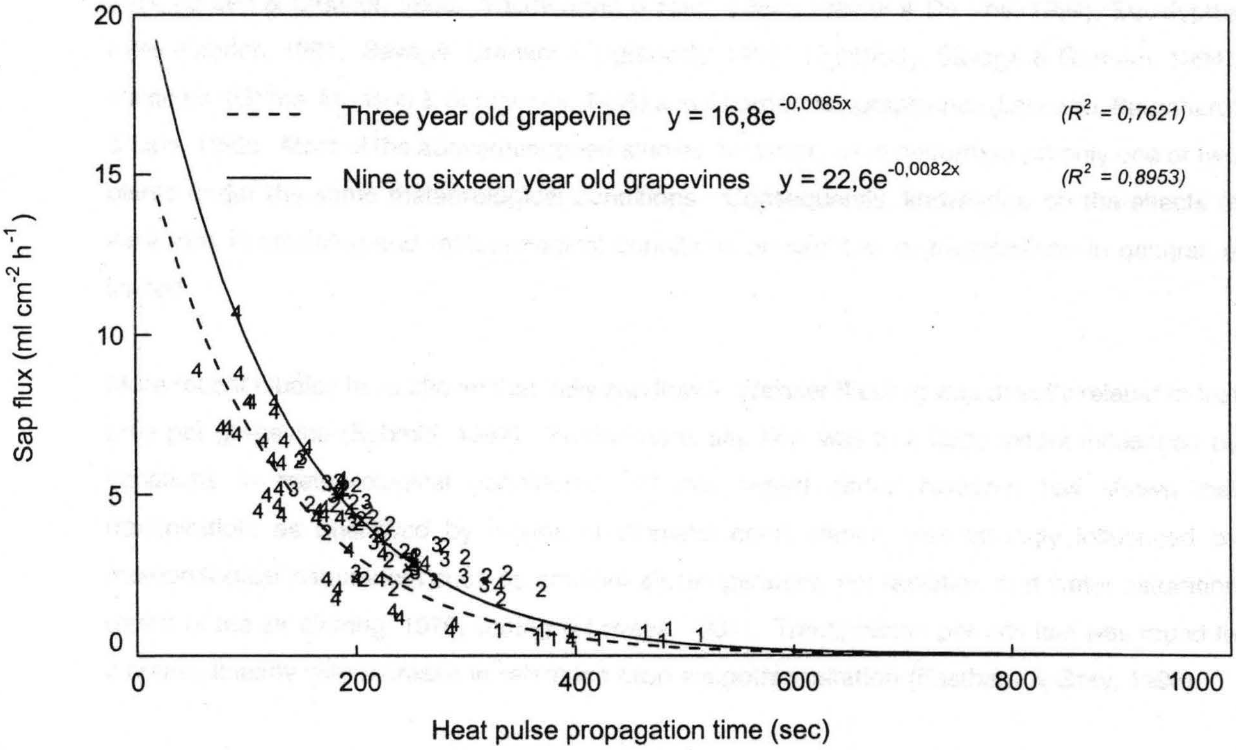

Figure 2.8. Calibration curves for measuring sap flux by means of the heat pulse velocity technique as determined in a three year old grapevine and in nine to sixteen year old grapevines (1 = Sultanina at Upington ; 2 = Barlinka at De Doorns ; 3 = Pinot noir at Stellenbosch ; 4 = 99 Richter at Stellenbosch).

CHAPTER 3

ESTIMATING DIURNAL SAP FLOW IN SOUTH AFRICAN VINEYARDS

3.1 INTRODUCTION

Evapotranspiration by vineyards is generally considered as a single process integrating evaporation and transpiration, which can be estimated by using three sets of pan crop coefficients (Green, 1985) and a reference crop evapotranspiration as proposed by Doorenbos & Pruitt (1977). However, research has shown that water consumption and pan crop coefficients can vary considerably between vineyards (Van Rooyen, 1980; Van Zyl & Weber, 1981; Van Zyl, 1984; Fourie, 1989; Myburgh, Van Zyl & Conradie, 1996). To understand why and how viticultural and meteorological conditions influence water consumption, transpiration and evaporation should be considered as individual parameters.

Development of techniques such as heat pulse velocity (Swanson & Whitfield, 1981) and stem heat balance (Baker & Van Bavel, 1987) made it possible to measure and quantify total daily sap flow or transpiration of single plants. By using either of these techniques, transpiration was quantified in kiwifruit (Edwards & Warwick, 1984; Green & Clothier, 1988; Green & Clothier, 1995), apple trees (Green & Clothier, 1988; Valancogne & Nasr, 1989; Weibel & De Vos, 1994), Eucalyptus trees (Olbrich, 1991; Savage, Graham & Lightbody, 1993; Lightbody, Savage & Graham, 1994), sunflower (Grime, Morison & Simmonds, 1995) and Chardonnay grapevines (Lascano, Baumhardt & Lipe, 1992). Most of the abovementioned studies, however, were performed on only one or two plants under the same meteorological conditions. Consequently, knowledge on the effects of variations in cropping and meteorological conditions on sap flow or transpiration in general, is limited.

More recent studies have shown that daily sap flow in Weisser Riesling was directly related to leaf area per grapevine (Schmid, 1997). Furthermore, sap flow was to a large extent influenced by variations in meteorological conditions. In this regard earlier research has shown that transpiration, as quantified by means of stomatal conductance, was strongly influenced by meteorological parameters such as ambient air temperature, net radiation and water saturation deficit of the air (Düring, 1976; Düring & Loveys, 1982). Transpiration per unit leaf was found to increase linearly with increase in reference crop evapotranspiration (Eastham & Gray, 1998).

Schmid (1997) reported that the rootstocks Kober 5BB, Selection Oppenheim 4, Börner and Sori had no significant effect on the daily sap flow of Weisser Riesling. Scion cultivar, however, can influence stomatal conductance and, consequently, daily sap flow rates. Stomatal conductance of Riesling grapevines was higher in comparison to Sylvaner grapevines under comparable meteorological conditions (Düring & Loveys, 1982). Furthermore, stomatal conductance of both cultivars was appreciably higher under humid, temperate meteorological conditions at Geilweilerhof, Germany, in comparison to semi-arid conditions at Adelaide, South Australia. This suggested that sap flow rates can vary according to climatic regions. However, it must be noted that the positive influence of higher stomatal conductance could, to a greater or lesser extent, be counteracted by lower evaporative demand under humid, temperate conditions.

The aim of this study was : (i) to determine how transpiration was influenced by viticultural and meteorological conditions, and (ii) to develop a model for estimation of diurnal transpiration by grapevine canopies.

3.2 MATERIALS AND METHODS

3.2.1 Experimental grapevines

To study the effect of parameters such as leaf area, canopy surface area orientation, irrigation, and removal of crop load on sap flow, a series of experiments were conducted in various vineyards. These vineyards were selected to be representative of cultivars, trellising systems, vine spacings and soil types generally found in South African grape growing areas. For the purpose of this study, these regions were classified according to the climatic conditions and parameters of the classification system developed specifically for viticulture by Winkler (1962).

Experiment 1 : The effect of leaf area on sap flow during early season was determined in a sixteen year old ungrafted Sultanina vineyard at the Upington Experimental Station of the Department of Agriculture Northern Cape in the Lower Orange River Valley. This locality is in a class V climatic region (Winkler, 1962) at 28° 27' latitude. Grapevines were planted 3,0 m x 1,5 m and trained onto a 2,4 m slanting trellis (Zeeman, 1981). The alluvial soil was of the Dundee form (Soil Classification Work Group, 1991). Three grapevines with comparable trunk diameter, bud load and canopy size were selected. Fourteen days prior to sap flow measurements, approximately 30 % and 60 % shoots and leaves of two respective grapevines were removed, resulting in 1,76 m^2 and 3,00 m^2 leaf area per vine. Shoots were removed evenly around the crown. The canopy of the third grapevine, which had a leaf area of 6,39 m^2, was left undisturbed. The vineyard was flood irrigated every two weeks. Sap flow measurements commenced one week after an irrigation. Sap flow measurements were carried out from 8 October until 11 October 1994, *i.e.* just prior to flowering.

Experiment 2 : A further experiment was conducted to study the effect of leaf area on sap flow during phase II of berry development. Three grapevines, varying in canopy size and in close proximity to each other, were selected in a sixteen year old Barlinka/Ramsey table grape vineyard at the ARC-Infruitec/Nietvoorbij Hex Valley Experimental Station near De Doorns. This locality is in a class V climatic region (Winkler, 1962) at 33° 28' latitude. Grapevines were planted 3,0 m x 1,8 m and trained onto a 2,4 m slanting trellis (Zeeman, 1981). The sandy soil, with a clay content of *ca* 5 %, was of the Fernwood form (Soil Classification Work Group, 1991). No canopy adjustment was performed prior to sap flow studies, which were carried out from 1 December until 5 December 1994. Grapevines, which were normally irrigated weekly by means of a 32 ℓ h^{-1} micro-sprinkler system, were irrigated two days before sap flow measurements began. No irrigation was applied during the sap flow study.

Experiment 3 : The effect of canopy size on sap flow in grapevines used for wine production was studied in an eight year old Pinot noir/99 Richter vineyard at the ARC-Nietvoorbij Centre for Vine and Wine near Stellenbosch. This locality is in a class III climatic region (Winkler, 1962) at 33° 54' latitude. Grapevines were planted 3,0 m x 1,5 m and trained onto a lengthened Perold system (Booysen, Steenkamp & Archer, 1992). This vineyard formed part of a rooting depth trial (Myburgh, Van Zyl & Conradie, 1996). Two grapevines were selected from the 400 mm and 1 200 mm rooting depth treatments. Canopy size varied according to soil depth. The granitic soil was of the Glenrosa form (Soil Classification Work Group, 1991). Due to a gravel content of 47 %, the soil had a relatively low plant available water content of 50 mm per meter (Myburgh *et al*, 1996). Consequently, grapevines were irrigated weekly by means of a 32 ℓ h^{-1} micro-sprinkler system. Sap flow studies were performed from 30 December 1994 until 3 January 1995, *i.e.* during phase II of berry development. Two irrigations were applied during the measurement period.

Experiment 4 : To obtain an indication of sap flow patterns in small vines, sap flow was also determined in the three year old potted 99 Richter rootstock used for the calibration of the heat pulse velocity technique as described in Chapter 2. This grapevine, with its limited canopy, was regarded to be representative of a small, vertically or horizontally trained plant. The grapevine was placed next to a production vineyard at the Nietvoorbij Centre for Vine and Wine. Climatic conditions were similar to those of Experiment 3. Sap flow was measured from 26 December until 29 December 1994. To avoid water stress, the grapevine was well watered one day prior to the sap flow measurements.

Experiment 5 : The effect of irrigation versus dryland conditions on sap flow was investigated in the same Pinot noir experimental vineyard where Experiment 3 was performed. Sap flow was measured both in a dryland and irrigated grapevine with comparable trunk diameter, crop load and canopy size. During the sap flow study, irrigation was applied at four day intervals by means of 32 ℓ h^{-1} micro-sprinklers (Myburgh *et al*, 1996). Sap flow was measured from 12 January until 20 January 1995, *i.e.* during ripening.

Experiment 6 : Leaf area effects on sap flow just prior to harvest were studied in the same Sultanina vineyard at Upington where Experiment 1 was performed. Three grapevines with different canopy sizes, in close proximity to each other, were selected and no canopy management was performed as for Experiment 1. Crop load varied according to canopy size (Myburgh, unpublished data). Sap flow was measured from 22 January until 27 January 1995. These grapevines formed part of an irrigation trial.

Experiment 7 : The effect of total bunch removal on sap flow was also studied one week before harvest in the Pinot noir vineyard at Stellenbosch where Experiments 3 and 5 were performed. However, in this experiment, trickle irrigated grapevines, which did not form part of the rooting depth trial, were used. Two grapevines with comparable trunk diameter, canopy size and yield were selected. Sap flow was measured from 31 January until 6 February 1995. On 3 February all the bunches of one grapevine were removed and weighed. Grapes of the remaining grapevine were harvested four days later. Yield as well as total soluble solids (TSS), total titrable acids (TTA) and pH of the must were determined. Water content of the grapes were also determined. To obtain dry mass, grapes were sun dried for ten days prior to drying at 60 °C. Water content (mass %) was calculated by dividing the water loss by the fresh mass.

Experiment 8 : The effect of canopy surface orientation on sap flow was studied on seven year old Emerald Riesling/110 Richter grapevines in a trellising systems field trial at the Robertson Experimental Station of ARC-Infruitec/Nietvoorbij. This locality is in a class V climatic region (Winkler, 1962) at 33° 50' latitude. Grapevines were planted 3,0 m x 1,5 m. Sap flow was measured in two grapevines with comparable trunk diameters. One grapevine was trained onto a vertical five-strand hedge (Booysen *et al*, 1992) and the other onto a 1,8 m slanting trellis (Zeeman, 1981). The clay loam soil was of the Garies form (Soil Classification Work Group, 1991). Grapevines were irrigated by means of 32 ℓ h^{-1} micro-sprinklers. However, no irrigations were applied during the sap flow experiment which was carried out from 8 February until 11 February 1995.

Experiment 9 : To quantify sap flow in a grapevine with a large, more or less vertically orientated canopy, sap flow was measured in a seven year old Emerald Riesling/110 Richter grapevine trained onto a 4,2 m Tatura trellising system (Van Den Ende, 1984). This grapevine was also part of the trellising systems trial at Robertson where Experiment 8 was performed. Plant spacing was 4,2 m x 1,5 m. Measurements were conducted from 28 March until 5 April 1995.

3.2.2 Leaf area

Directly after each sap flow experiment, all leaves were removed from experimental grapevines. Total leaf area was determined by means of a leaf area meter (Li 3100, Li-Cor). In the case of Experiments 3 and 8, sap flow recording was continued for six hours after leaf removal.

3.2.3 Sap flow

This parameter was determined by means of the heat pulse velocity technique. Four sensors were installed in the trunk wood (xylem) as described in Chapter 2. Sap flow was recorded at 15 minute intervals using a specially designed heat pulse generation and temperature measurement system (Micro Innovations, Pretoria). Hourly average values were calculated from these data. Trunk diameters were measured at points where sensors were installed. Heat pulse propagation time (seconds) was converted to hourly sap flow (ml $h^{-1}vine^{-1}$) by means of the empirical calibration curves established for grapevine trunks presented in Chapter 2. Hourly sap flow values were summed over 24 hours and divided by 10^3 to obtain diurnal sap flow ($\ell.d^{-1}.vine^{-1}$)

3.2.4 Meteorological parameters

Daily American Class A-pan evaporation (E_p) was obtained from meteorological stations at the Upington, Hex River Valley, Nietvoorbij and Robertson Experimental stations. All meteorological stations were within 1 km from the sites where sap flow experiments were performed. Hourly net radiation, wet and dry bulb air temperature as well as wind speed were obtained using automatic weather stations (MC-Systems) at the same localities. Hourly reference crop evapotranspiration (ET_o) was calculated from these parameters by means of a modified Penman-Monteith equation as follows (De Jager *et al*, 1987) :

$$ET_o = 3600\ [s\ (Qn - G)\ /\ (s + \gamma^*) + (Cp\ \delta e\ \phi a)\ /\ (s + \gamma^*)]\ /\ L \qquad (3.1)$$

where : ET_0 = reference crop evapotranspiration (mm h^{-1})

s = slope of saturated vapour pressure temperature curve (Pa $°C^{-1}$)

Qn = net radiation (W m^{-2})

G = soil heat flux density (W m^{-2})

γ^* = psychrometric constant influenced by temperature and wind (Pa $°C^{-1}$)

Cp = specific heat of air (J kg^{-1} $°C^{-1}$)

δe = difference between the saturated vapour pressure and vapour pressure of air at a specific temperature (mbar)

ϕa = aerodynamic conductance of the atmosphere (m s^{-1})

L = latent heat of evaporation of water (J kg^{-1})

and 3600 ensures coherency of units. The psychrometric constant influenced by temperature and wind, γ^*, is calculated as follows:

$$\gamma^* = \gamma(1 + \phi_a/\phi_v) \tag{3.2}$$

where : γ = psychrometric constant (Pa °C^{-1})

ϕa = aerodynamic conductance of the atmosphere (m s^{-1})

ϕv = whole crop surface conductance for water vapour exchange (0,03 m s^{-1})

The aerodynamic conductance of the atmosphere is calculated as follows:

$$\phi a = k^2\, u(z) \;/\; (\ln(2\text{-}d)/z_o)^2 \tag{3.3}$$

where : k = Von Karman's constant (0,41)

u(z) = windspeed at 2 m height (m s^{-1})

z = height at which measurements were made (m)

d = zero plane displacement level (m)

z_o = surface roughness parameter (m)

In equation 3.3, z_o is 0,013 m and d is 0,063 m for a reference crop height of 0,1 m (Van Zyl, De Jager & Maree, 1989). Measurements were made at a height of 2,0 m. Hourly ET_o values were summed over 24 hours to obtain daily ET_o.

3.3 RESULTS AND DISCUSSION

3.3.1 Effect of leaf area

During the early part of the growing season, hourly sap flow rates in the three Sultanina grapevines at Upington (Experiment 1) tended to be erratic during the day (Fig. 3.1A). Since this effect also occurred in the grapevine where no shoots were removed, physiological disturbance due to canopy manipulation could not have caused this phenomenon. Furthermore, skies were cloudless and virtually no wind occurred during sap flow measurements, which suggested that the erratic flow was probably a natural response to changes in canopy microclimate, *e.g.* light, wind and humidity. Despite the variability in hourly sap flow rates, cumulative sap flow increased with increasing leaf area, which was 1,76 m^2, 3,00 m^2 and 6,39 m^2 for the respective grapevines (Fig. 3.1B). This effect of leaf area was confirmed when sap flow was measured in three Barlinka grapevines where no canopy manipulations were performed (Experiment 2). Leaf area was 3,24 m^2, 9,56 m^2 and 13,74 m^2 for the respective grapevines. Hourly sap flow rates in these grapevines (Fig. 3.2), however, were more stable during the day compared to the Sultanina grapevines in Experiment 1. Short term day-time changes in canopy microclimate probably reduced as leaf density increased. In comparison to a leaf area of 7,16 m^2, the 10,88 m^2 canopy, which was induced by deeper soil preparation (Experiment 3), also resulted in higher hourly sap flow rates in Pinot noir grapevines (Fig. 3.3). Similar to the results of Experiment 1, hourly sap flow measured in the same Sultanina vineyard prior to harvest (Experiment 6), tended to be erratic during the course of the day (Fig. 3.4A). At this stage leaf area of the fully developed canopies were 5,22 m^2, 7,60 m^2 and 10,25 m^2 respectively, for the three grapevines. In this case cumulative sap flow also increased with leaf area despite the erratic hourly flow rates during the day (Fig. 3.4B).

The strong dependency of total diurnal sap flow on leaf area, irrespective of cultivar, was in agreement with the findings of Eastham & Gray (1998). Hourly sap flow rates measured in Weisser Riesling under humid, temperate meteorological conditions in Germany (Schmid, 1997), however, were notably higher compared to values for grapevines with comparable leaf area as measured in this study under semi-arid conditions. The higher sap flow rates measured in Germany were in agreement with the higher stomatal conductance under humid, temperate meteorological conditions compared to semi-arid conditions reported by Düring & Loveys (1982). This suggests that the transpiration component of crop coefficients may be higher under humid, temperate conditions than under semi-arid conditions. The strong relationship between sap flow and leaf area observed in the abovementioned studies proved that transpiration was closely related to leaf area and that crop coefficients for grapevines will increase with an increase in leaf area.

3.3.2 Effect of irrigation

In comparison to non-irrigated Pinot noir grapevines, irrigation only resulted in slightly higher hourly sap flow rates during the day (Experiment 5). On days when grapevines were irrigated, hourly sap flow showed relatively high peaks (Fig. 3.5). These sap flow peaks, which occurred shortly after the start of an irrigation, was probably due to increased water uptake to regain turgidity of plant cells. If increased water availability during an irrigation would have increased transpiration, sap flow would have remained at the peak level throughout most of the day. This suggested that sap flow was only significantly increased when high soil water matrix potential under saturated conditions allowed high water uptake rates by the grapevine roots. A slightly higher leaf area of 10,86 m^2 of the irrigated grapevine in comparison to 9,96 m^2 of the non-irrigated grapevine could also have caused the slightly higher hourly sap flow rates observed between irrigations. Relatively low hourly sap flow rates of both irrigated and non-irrigated grapevines were probably caused by small canopies as well as the low plant water availability of this specific soil (Myburgh *et al*, 1996).

3.3.3 Effect of total leaf removal

After total leaf removal during the day in Experiment 3, hourly sap flow declined rapidly to rates comparable to the lowest values measured during the previous nights (Fig. 3.3). Similar results were obtained when leaves were removed at 10:00 from the Emerald Riesling grapevine in Experiment 9 (Fig. 3.6). The sharp decrease in sap flow rate after leaf removal also proved that during the day sap flow was primarily a function of transpiration.

3.3.4 Effect of total grape removal

Removing the total crop load of Pinot noir grapevines during ripening (Experiment 7), had no significant effect on hourly sap flow rates (Fig. 3.7). Juice analyses showed that on 3 February, TSS and TTA were 21,1 °B and 11,1 g ℓ^{-1}, respectively. Four days later the same parameters were 22,6 °B and 10,0 g ℓ^{-1}. Grapes were near maturity and, notwithstanding a yield equivalent to *ca* 30 t ha^{-1}, probably did not act as a strong sink for water. Furthermore, considering that a water content of 68 % in 30 tons of grapes is equivalent to 6 mm per season, grapes might not be a strong sink for water at any stage. These results indicated that during ripening sap flow could be regarded as primarily being a function of leaf area.

These results further suggested that an increase in crop load would not necessarily lead to higher water consumption rates by grapevines if leaf areas were comparable. However, replenishment of water lost by bunches during the day (Van Zyl, 1984), would probably induce higher water stress levels at higher crop loads. To avoid this by more frequent irrigation will increase water consumption due to increased evaporation from the soil surface as well as higher transpiration rates. Hence, the increased water consumption would not be a sole function of the water actually required to produce bunch mass.

3.3.5 Sap flow during the night

Sap flow in grapevines also occurred during the night. These hourly rates were relatively low in comparison to rates measured in full sunshine. Replenishment of day time water deficits, which were caused by water uptake being slower than transpiration losses during the day, could be the reason for sap flow during the night. This is in agreement with grapevine trunk contraction and expansion that normally occur during the day and night, respectively (Myburgh, 1996). Substantial sap flow at night to refill internal plant water, was also measured in water-stressed grapevines (Eastham & Gray, 1998) as well as Asian pear trees (Caspari, Green & Edwards, 1993). Night time sap flow rates tended to increase with increasing leaf area (Fig. 3.2, 3.3 & 3.4A). This indicated that the absolute amount of water deficit that had to be replenished during the night, increased with canopy size.

3.3.6 Effect of meteorological conditions

Stomatal opening of grapevines is controlled by light. Transpiration rates generally follow diurnal net radiation patterns (Düring, 1976). Consequently, cloudy weather caused a decrease in hourly sap flow rates measured in Experiment 2 when light rain and overcast conditions prevailed during 5 December 1994 (Fig. 3.8). Hourly sap flow as measured in the three Barlinka grapevines in Experiment 2 was strongly related to hourly net radiation (Fig. 3.9). Sap flow, however, did not respond linearly to net radiation. This suggested that stomatal control, *i.e.* partial stomatal closure at higher radiation loads, only allowed a certain amount of water loss, causing sap flow to vary asymtotically around a maximum velocity. This threshold for stomatal regulation was reached at net radiation intensities of *ca* 2 MJ m^{-2} h^{-1}. Hourly sap flow measured in Pinot noir grapevines (Experiment 3) responded similarly to net radiation (Fig. 3.10). These results indicated that increased soil water availability at relatively high matrix potential values would probably not result in unlimited increases in hourly sap flow rates.

In the case of the Sultanina grapevine with the largest leaf area (Experiment 6), hourly sap flow rate increased with net radiation from sunrise until 08:00. This was followed by a slight decrease up to 10:00 and a more pronounced decrease up to 12:00 (Fig. 3.11A). The decrease in sap flow rate continued, notwithstanding the fact that net radiation continued to increase until *ca* 13:00. Sap flow tended to recover between 13:00 and 14:00. The decrease observed at 15:00 could be due to plant water stress. Despite the normal decrease in net radiation during the afternoon, sap flow rate showed an increase up to 17:00. This was followed by a continued decrease until sunset.

In the case of the second Sultanina grapevine in Experiment 6 (7,60 m^2 leaf area), hourly sap flow showed similar tendencies. However, sap flow seemed to recover earlier and over a longer period, *i.e.* from 12:00 until 15:00, followed by a decrease probably also caused by plant water stress (Fig. 3.11B). Hourly sap flow rate of the third grapevine (5,22 m^2 leaf area) tended to recover between 11:00 and 14:00. Albeit, in this case a pronounced decrease occurred from 14:00 until 16:00, possibly due to even higher plant water stress (Fig. 3.11C). Monitoring of plant water stress on 24 January 1995 by means leaf water potential at 15:00, which was part of an irrigation trial in the same vineyard, indeed revealed that the second and third grapevines, which were irrigated by means of the alternative row method, were under more water stress (-1965 kPa) compared to the first where full surface irrigation was applied (-1605 kPa) (Myburgh, Unpublished data).

Considering that cloudless skies allowed normal radiation, the temporary decrease in hourly sap flow rate generally observed between 09:00 and 16:00 could not have been caused by variations in meteorological conditions. This suggested that the lower sap flow rates were the result of a possible water saving mechanism causing stomatal closure under warm and dry meteorological conditions. Erratic hourly sap flow during day-time recorded in three grapevines earlier in the season (Fig. 3.1A) was probably also the result of stomatal closure. These results were in agreement with the findings of Düring & Loveys (1982). Doorenbos & Pruitt (1977) also suggested that grapevines have a greater degree of stomatal control compared to many other crops which contributes to the relatively low K_{cp} values for vineyards.

Reference crop evapotranspiration (ET_o), which is also a function of net radiation, was therefore similarly related to hourly sap flow in the Barlinka and Pinot noir grapevines (Fig. 3.12). Generally hourly sap flow rates showed almost no increase when ET_o exceeded 0,4 mm h^{-1}. This suggested that, in addition to the magnitude of hourly ET_o, the length of time at which this parameter was maintained above 0,4 mm h^{-1} also determined the total amount of sap flow during the day.

3.3.7 **Effect of canopy surface orientation**

In general, hourly sap flow rates measured in grapevines with vertically orientated canopy surfaces, *i.e.* Perold and Tatura, tended to be lower compared to horizontally orientated canopy surfaces with comparable leaf area (Fig. 3.13). In the case of vertical canopy surfaces, theoretically only about half of the outer leaf layer of the canopy can be exposed to the full radiation intensity on normal sunshine days. This suggested that less leaf area was exposed to net radiation causing lower transpirational water losses which resulted in lower hourly sap flow rates compared to horizontally orientated canopy surfaces where most of the outer leaves were exposed to radiation throughout the day.

The relatively high diurnal sap flow of the Emerald Riesling grapevine on the vertical trellis (11,91 m^2) (Experiment 8) was due to inaccurate sap flow measurement caused by malfunctioning of the heat pulse velocity equipment (Fig. 3.13). Although four probes were installed as recommended in Chapter 2, only the two outermost probes functioned properly. Since these probes were installed in the younger xylem, where the highest sap flux generally occur, sap flow measurements were not representative of the total xylem. Hence, sap flow was probably overestimated. For the purpose of this study, the values obtained for this grapevine were regarded as outliers and ignored as such. Sap flow data obtained for the Emerald Riesling grapevine on the 1,5 m slanting trellis (14,92 m^2), where sap flow was measured correctly, were in line with diurnal sap flow measured in other grapevines on horizontal canopies. Diurnal sap flow of the Emerald Riesling grapevine on the Tatura trellis (14,13 m^2) (Experiment 9) was also in line with data obtained for the other grapevines on vertical canopies. These results proved that the outliers were not caused by differences in sap flow characteristics between Emerald Riesling and other cultivars used in this study.

3.3.8 Sap flow *vs* transpiration

The close relationship between sap flow and leaf area per grapevine, the sharp reduction in sap flow after total leaf removal, as well as the fact that sap flow was not significantly reduced after crop removal, showed that sap flow is predominantly a function of transpiration losses. Hence, for the modelling purpose of this study, sap flow will be regarded to be equal to transpiration.

3.3.9 Predicting total daily sap flow or transpiration

From the foregoing it was clear that the amount of total daily sap flow or transpiration was primarily determined by leaf area per grapevine, canopy surface orientation and the effect of meteorological conditions on stomatal opening. Consequently, when only these parameters were considered, variation in daily transpiration could to a large extent be explained by means of multiple linear regression. Although sap flow did not respond linearly to hourly ET_o during the of course of the day (Fig. 3.12), the fact that including daily ET_o in the linear equation improved estimation of daily sap flow, suggests some linearity between these two parameters on a daily basis. In practice, this means that sap flow will decrease according to the duration of adverse meteorological conditions, *e.g.* cloudy skies, compared to normal sunshine days when the maximum amount of sap flow as determined by leaf area per grapevine, canopy surface conditions and stomatal control will occur. This also implies that sap flow will not increase indefinitely with an increase in daily ET_o.

Due to the tendency towards differences in transpiration caused by canopy orientation, data of the horizontal and vertical canopies were treated separately. This allowed more accurate prediction of variation in transpiration (Fig. 3.14 & 3.15). In the case of horizontal canopies variation in diurnal sap flow could be explained by the following multiple linear regression model:

$$Q_H = 0{,}338LA + 0{,}072E_p - 0{,}443 \qquad (R^2 = 0{,}9085;\ n = 36) \qquad (3.4)$$

where Q_H is sap flow per grapevine ($\ell\ d^{-1}\ vine^{-1}$) for horizontal canopies, LA is leaf area per grapevine (m^2) and E_p is Class A-pan evaporation ($mm\ d^{-1}$). The various grapevines of which the data were used to develop equation 3.1 were either on own roots (Sultanina at Upington) or grafted onto Ramsey (Barlinka at De Doorns) or 110 Richter (Emerald Riesling at Robertson). Under the conditions of this study, sap flow was primarily a function of leaf area, canopy surface orientation and meteorological conditions. Hence, it can be assumed that in this study different rootstocks had little effect on sap flow in comparison to own roots. This is in agreement with the findings of Schmid (1997). However, larger leaf areas resulting from vigour induced by specific rootstock cultivars, *e.g.* Ramsey, will increase diurnal sap flow in comparison to less vigorous rootstocks under comparable viticultural and meteorological conditions.

Diurnal sap flow in vertical canopies (Q_V) could be described by the following equation:

$$Q_V = 0{,}200LA + 0{,}043E_p - 0{,}433 \qquad (R^2 = 0{,}8596;\ n = 43) \qquad (3.5)$$

where LA is leaf area per grapevine (m^2) and E_p is American Class A-pan evaporation ($mm.d^{-1}$). However, Class A-pans are systematically being replaced by automatic weather stations which allow the calculation of a reference crop evapotranspiration (ET_o) by means of the Penman-Monteith equation. When ET_o values ($mm\ d^{-1}$) were used in the multiple linear regression, equations (3.4) and (3.5) changed to :

$$Q_H = 0{,}331LA + 0{,}1854ET_o - 1{,}140 \qquad (R^2 = 0{,}9226;\ n = 36) \qquad (3.6)$$

for estimating diurnal sap flow in horizontal grapevine canopies and,

$$Q_V = 0{,}199LA + 0{,}065ET_o - 0{,}401 \qquad (R^2 = 0{,}8583;\ n = 43) \qquad (3.7)$$

for estimating sap flow in vertical grapevine canopies.

Since most of the grapevines used to develop the abovementioned sap flow models were irrigated, it must be assumed that no or very little water stress occurred. Hence, application of the models would be limited to no stress conditions or at least conditions where water stress does not have negative effects on grapevine physiology. However, in irrigated vineyards this might not be a serious shortcoming since grapevines are normally irrigated to avoid excessive water stress. Where grapevines are grown dryland, excessive water stress will most likely reduce sap flow and consequently limit model accuracy.

3.4 CONCLUSIONS

Measuring sap flow by means of the heat pulse velocity technique revealed that the amount of diurnal sap flow increased with leaf area. Due to more outer leaf layers exposed to radiation, hourly sap flow rates measured in horizontally orientated canopies tended to be higher in comparison to vertical canopies with comparable leaf area. Generally, hourly sap flow did not increase linearly with net radiation which suggested that maximum stomatal opening only allowed a fixed amount of transpiration, irrespective of increased net radiation. Furthermore it was found that, hourly sap flow rates in Sultanina grapevines at Upington showed a temporary decrease during the day, irrespective of increasing net radiation. This suggested a possible water saving mechanism resulting from stomatal closure at high light intensities during mid-day.

After total leaf removal during the day, hourly sap flow decreased rapidly to values measured during the night. Hence, transpiration primarily contributes to sap flow during the day. Removing the total crop load during ripening had no effect on sap flow which indicated that bunches did not significantly contribute towards sap flow at that stage. Factors such as crop load and irrigation had limited effects on total diurnal sap flow compared to leaf area canopy orientation and meteorological conditions. Due to these findings, sap flow was assumed to be equal to transpiration losses. In comparison to non-irrigated grapevines, irrigation only tended to increase hourly sap flow slightly. However, during an irrigation, initially high flow peaks indicated that, in addition to increased transpiration, cell water was replenished to regain turgidity. Results also revealed that increased soil water availability would not necessarily result in unlimited increases in sap flow or transpiration.

Eighty percent of variation in total diurnal sap flow could be explained by means of linear regression when only leaf area per grapevine, canopy surface orientation and reference crop evaporation (ET_o) or Class-A pan evaporation (E_p) were considered. However, due to differences in the amount of leaves exposed to direct net radiation, variation in sap flow was explained more accurately by individual linear models for horizontal and vertical canopies, respectively. In the case of vertical canopies however, the model tended to underestimate daily sap flow in canopies with high leaf area per grapevine. At this stage there is no explanation for this tendency. The correlation coefficients obtained for these models confirmed that they would be reliable to predict sap flow or transpiration as a component of total diurnal evapotranspiration by vineyards, provided that high radiation loads do not bring about excessive stomatal regulation. However, since the increase in shading with increase in leaf layers, cultivar characteristics and locality effects were not accounted for, these models are regarded as a first approach. Furthermore, it must be noted that application of the models would be valid for irrigated vineyards where no or limited water stress is expected. To obtain a more accurate model, these parameters should be considered in further research to refine estimation of sap flow or transpiration. On the other hand, it must also be realized that any model becomes more complex as the number of inputs increase. Therefore, the objective of future research should be to find a balance between acceptable accuracy and the simplicity of the model.

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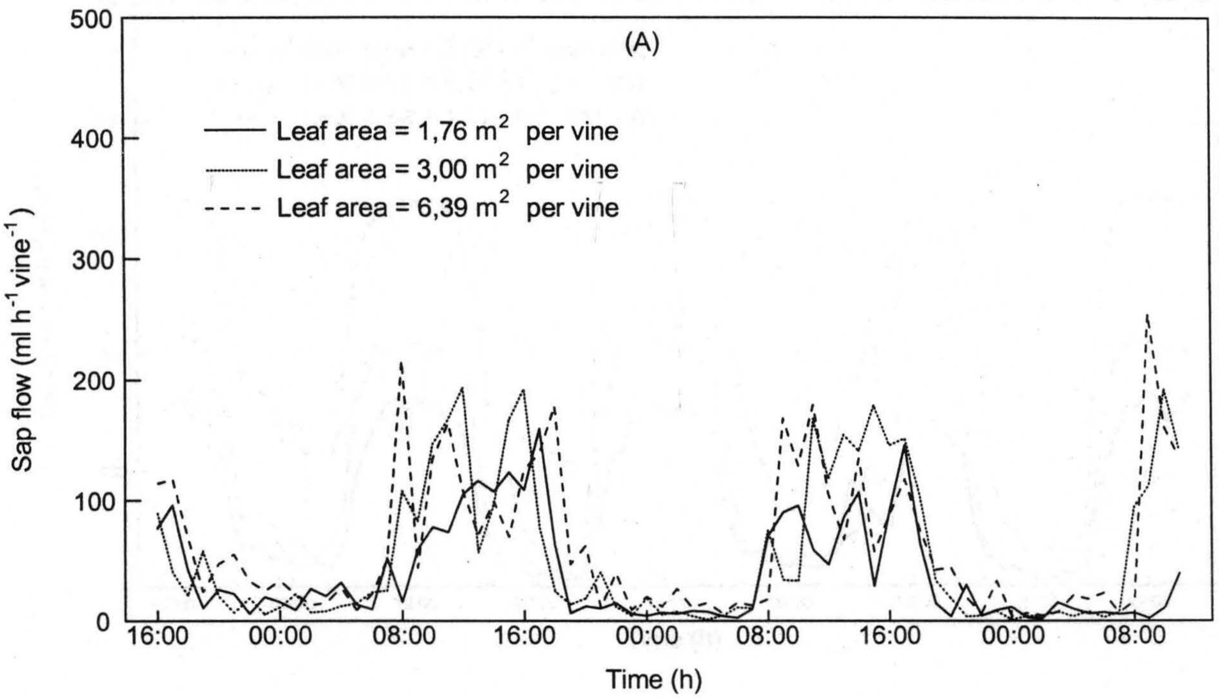


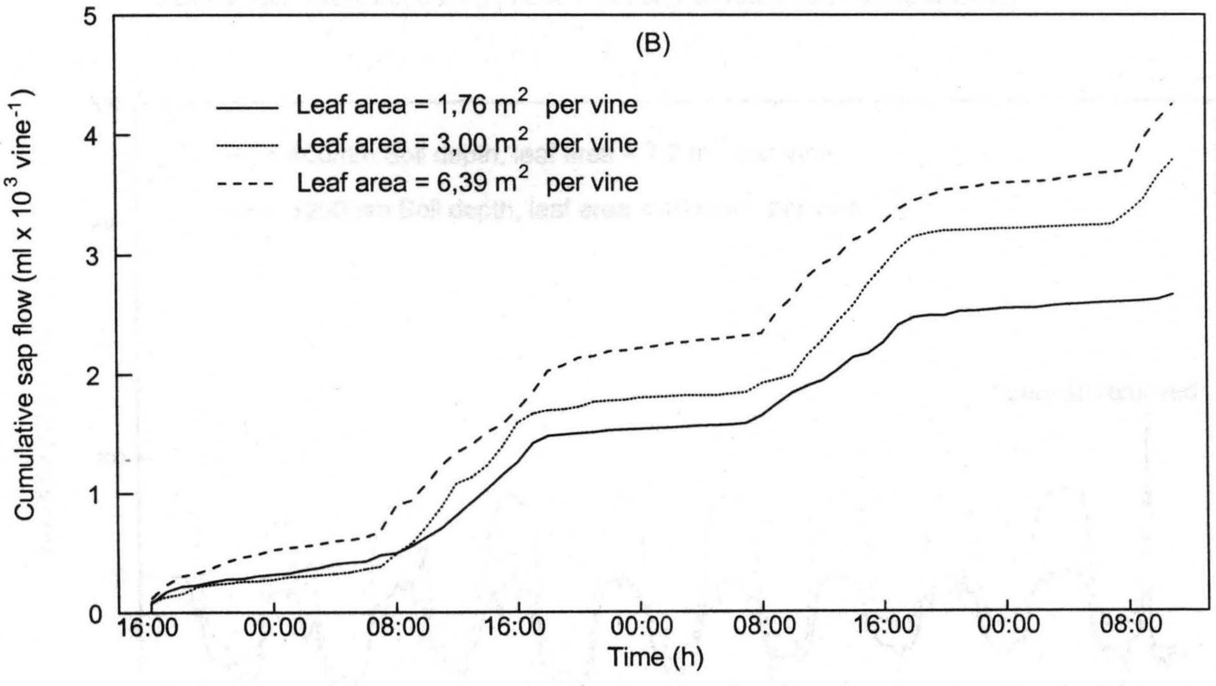


Figure 3.1. Effect of leaf area per grapevine on (A) hourly sap flow rate and on (B) cumulative sap flow in sixteen year old, flood irrigated Sultanina grapevines on a 2,4 m slanting trellis as measured from 8 October until 11 October 1994, *i.e.* prior to flowering, at Upington.

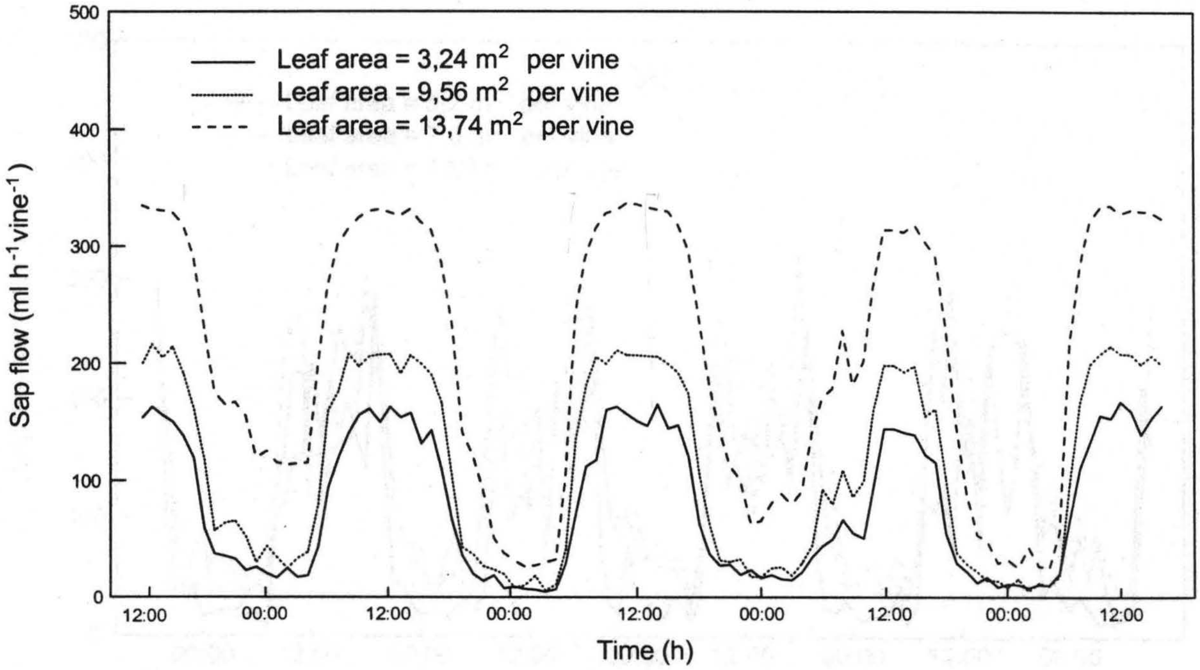


Figure 3.2. Effect of leaf area per grapevine on hourly sap flow rate in sixteen year old, micro-sprinkler irrigated Barlinka grapevines on a 2,4 m slanting trellis as measured from 1 December until 5 December 1994, *i.e.* during phase II of berry development, at De Doorns.

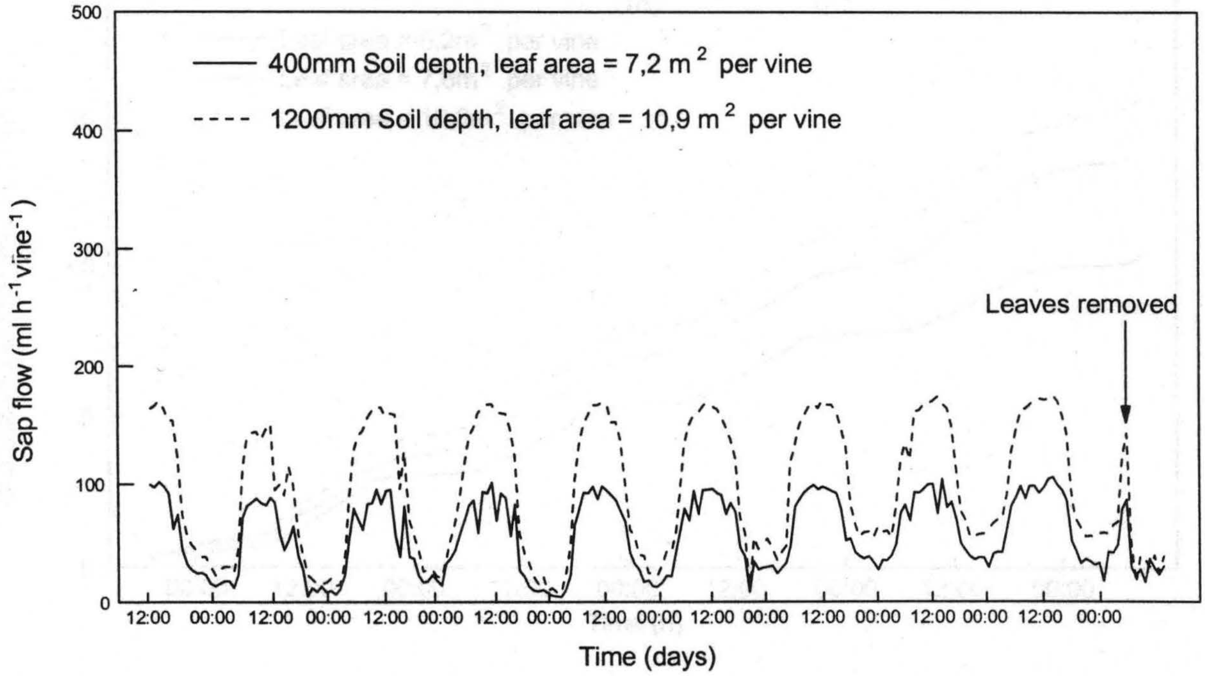
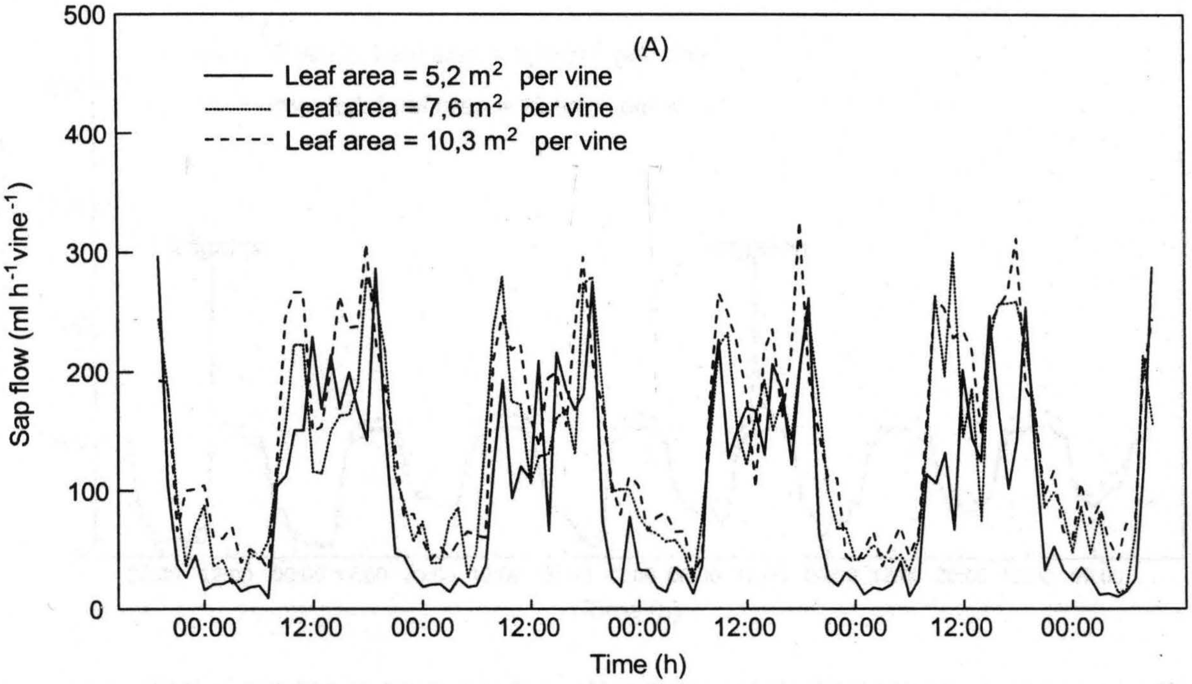


Figure 3.3. Effect of leaf area per grapevine, as induced by soil depth, on hourly sap flow in eight year old, micro-sprinkler irrigated Pinot noir grapevines on a lengthened Perold trellis as measured between 30 December 1994 and 8 January 1995, *i.e.* during phase III of berry development, at Stellenbosch.



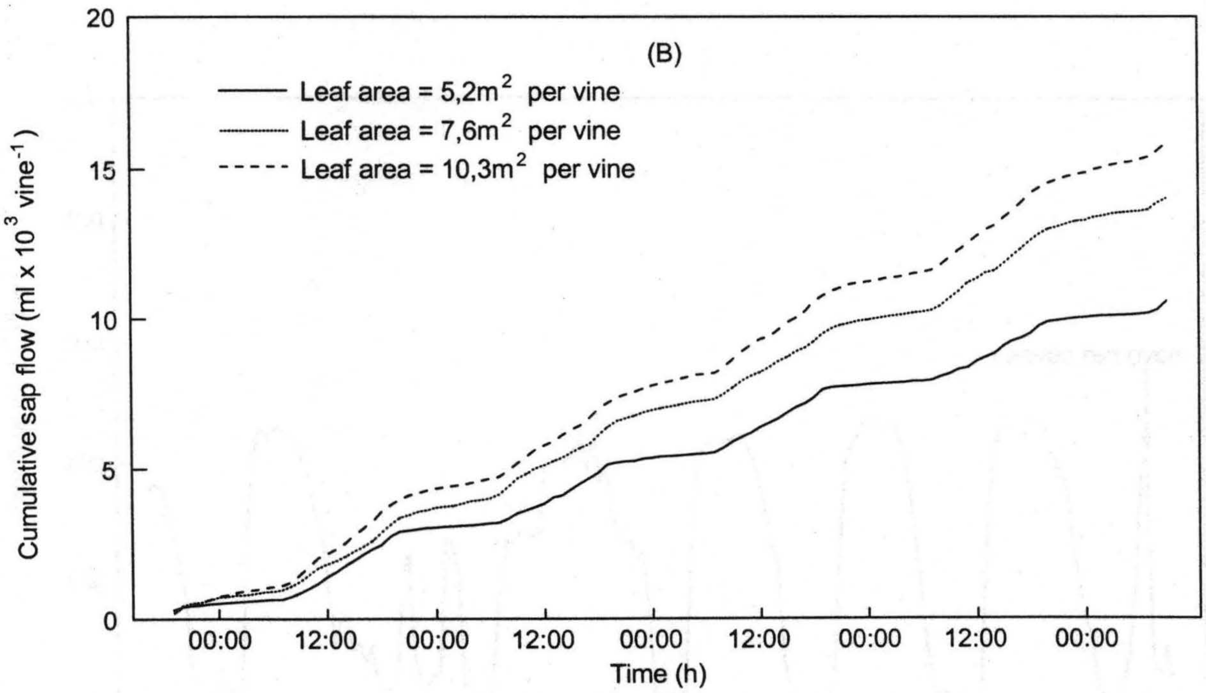


Figure 3.4. Effect of leaf area per grapevine on (A) hourly sap flow rate and (B) cumulative sap flow in sixteen year old, flood irrigated Sultanina grapevines on a 2,4 m slanting trellis as measured from 22 January until 27 January, *i.e.* just prior to harvest, 1995 at Upington.

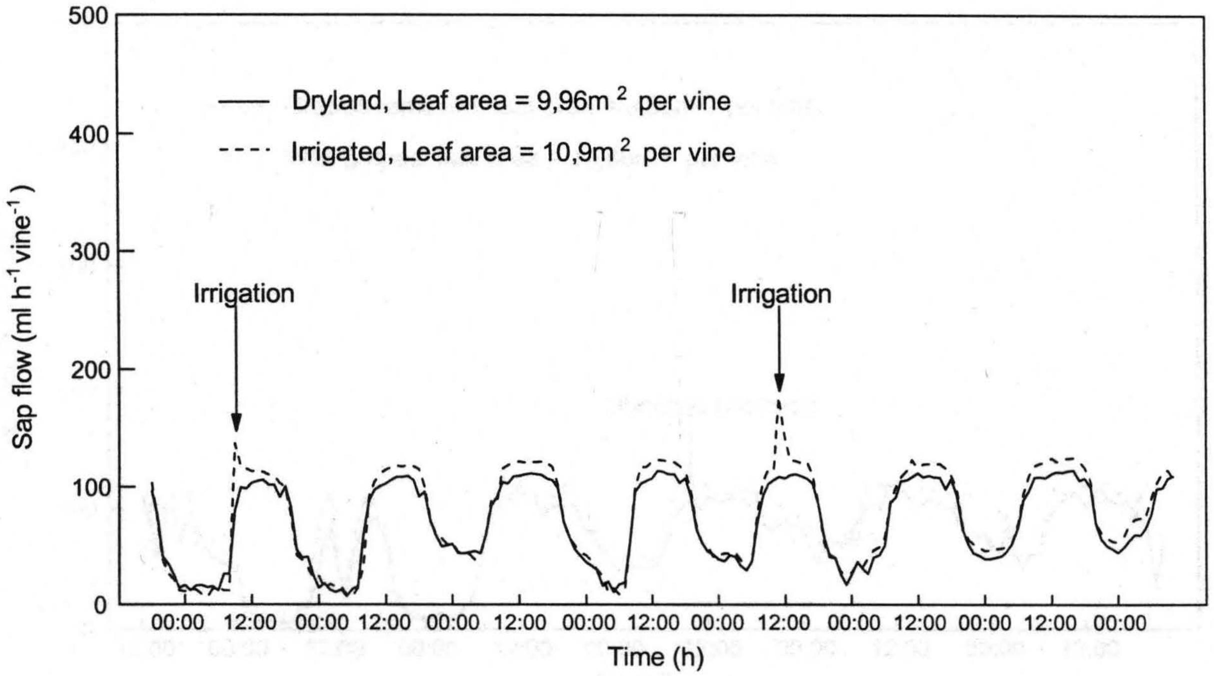


Figure 3.5. Effect of irrigation on hourly sap flow rate in eight year old Pinot noir grapevines on a lengthened Perold trellis as measured from 12 January until 20 January 1995, *i.e.* during ripening at Stellenbosch.

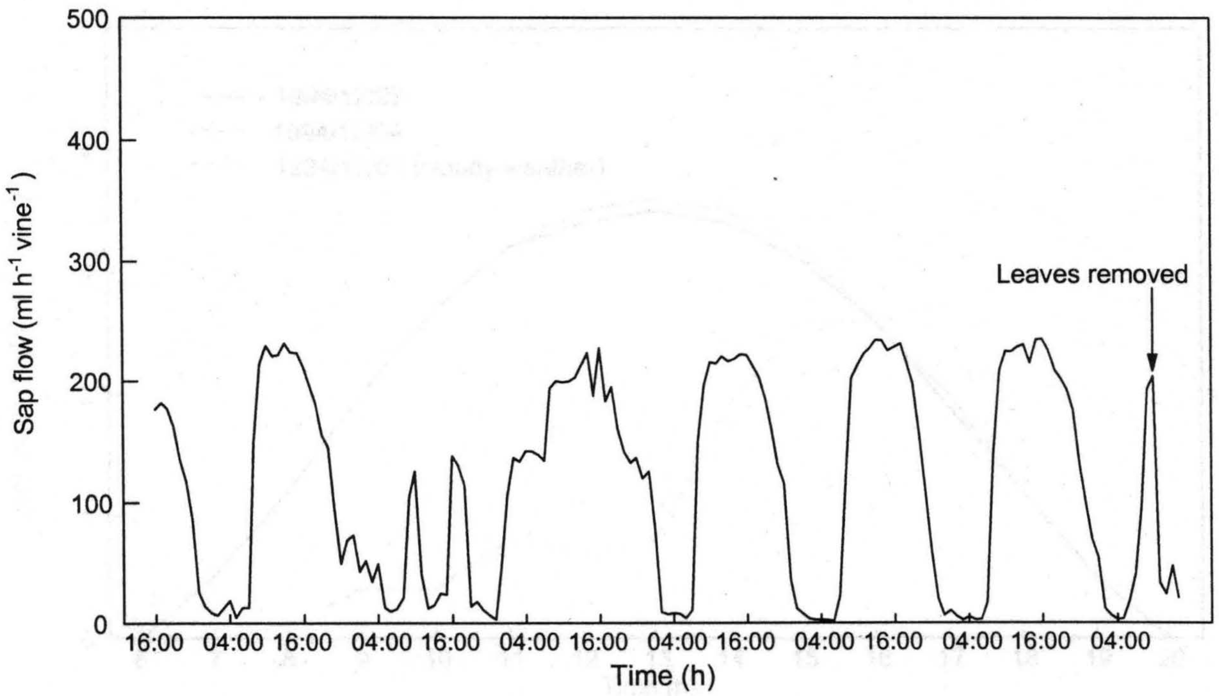


Figure 3.6. Hourly sap flow rate in a seven year old, micro-sprinkler irrigated Emerald Riesling grapevine trained onto a Tatura trellising system as measured from 2 April until 8 April 1995, *i.e.* during the post harvest period, at Robertson.

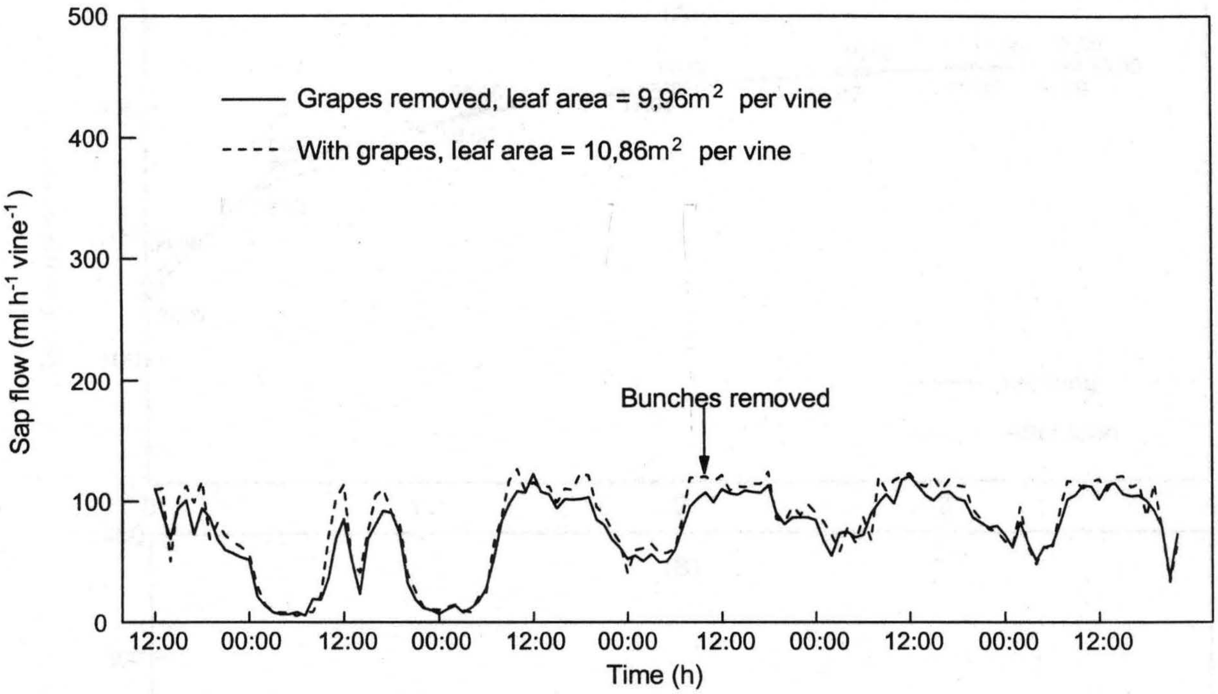


Figure 3.7. Effect of total bunch removal during ripening on hourly sap flow rate in eight year old, drip irrigated Pinot noir grapevines on a lengthened Perold trellis as measured from 31January until 6 February 1995, *i.e.* one week prior to harvest, at Stellenbosch.

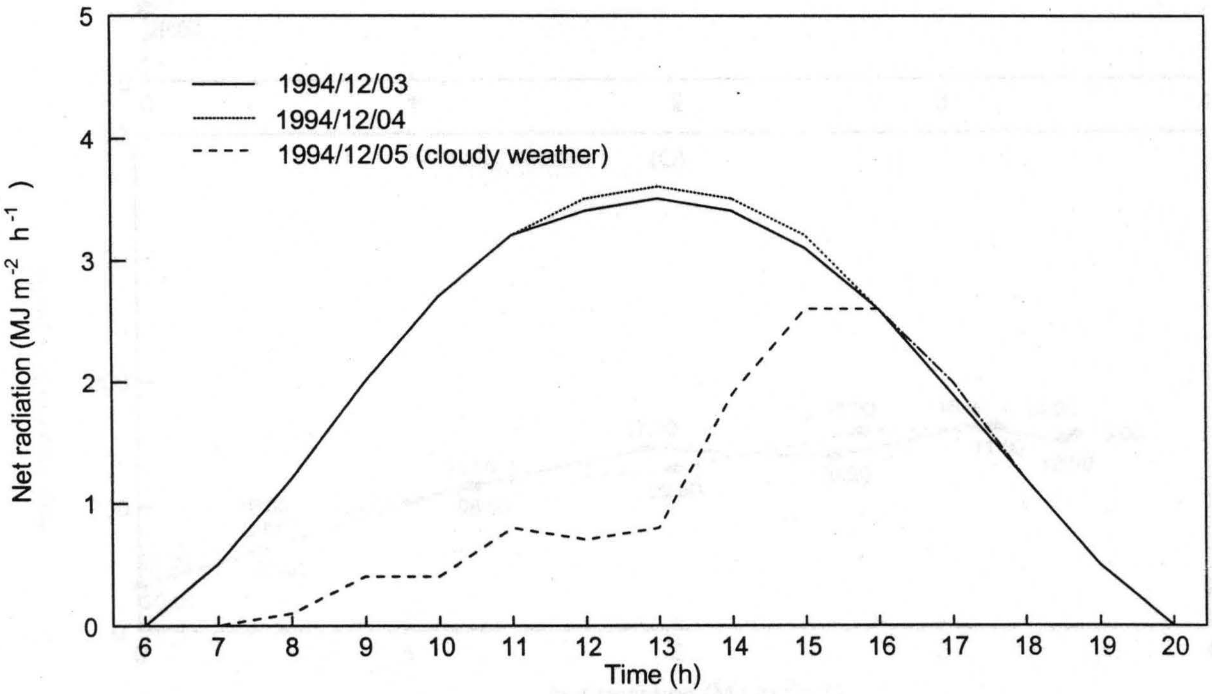


Figure 3.8. Effect of cloudy weather on daily net radiation as measured during an investigation to determine sap flow under different conditions in sixteen year old, micro-sprinkler irrigated Barlinka grapevines on a 2,4 m slanting trellis at De Doorns during phase II of berry development.

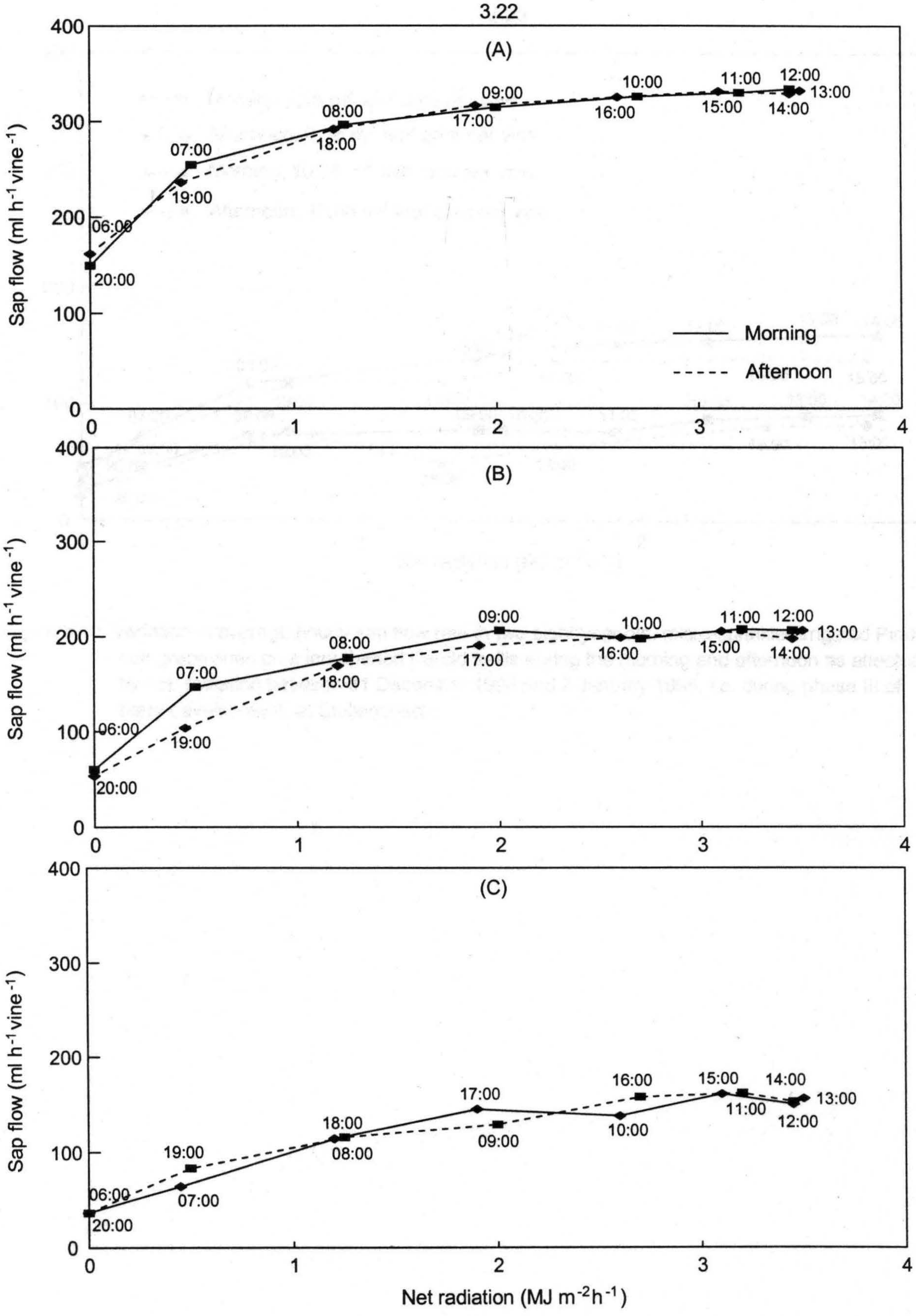


Figure 3. 9. Average diurnal variation of hourly sap flow rate in three sixteen year old, micro-sprinkler irrigated Barlinka grapevines on a 2,4 m slanting trellis during the morning and afternoon as affected by net radiation as measured on 2 and 3 December 1994, *i.e.* during phase II of berry development, at De Doorns. Total leaf areas of grapevines were (A) 13,74 m^2, (B) 9,56 m^2 and (C) 3,24 m^2.

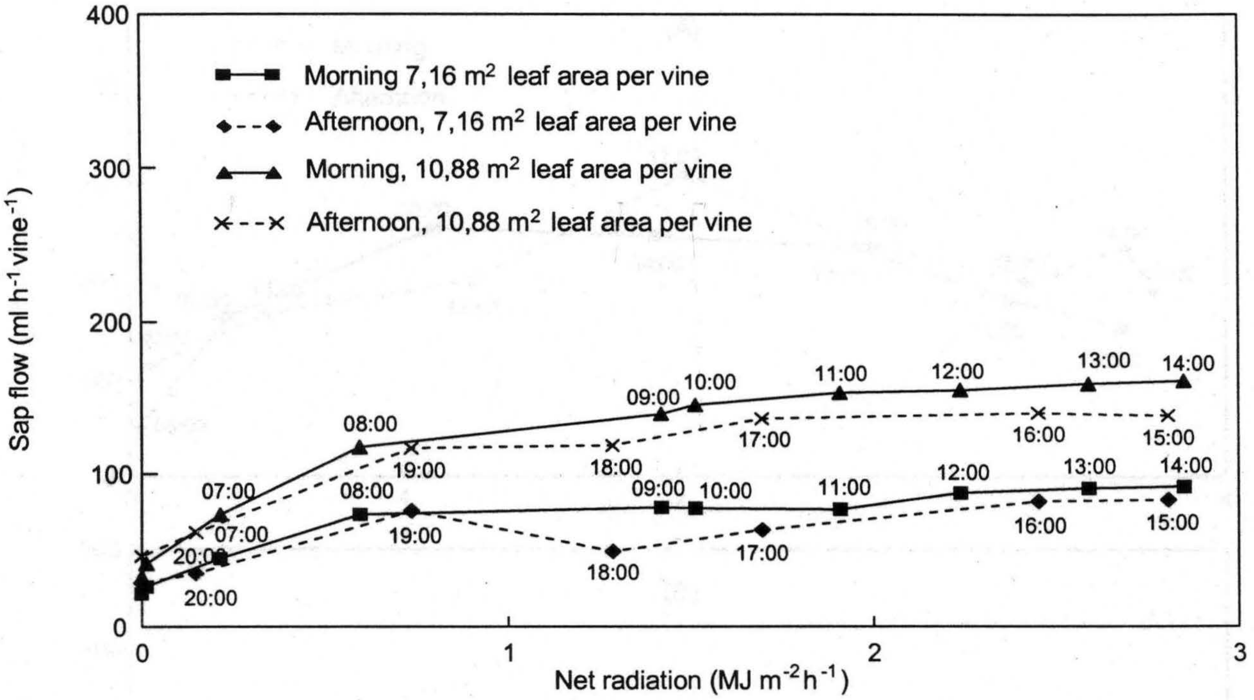


Figure 3.10. Variation in average hourly sap flow rate in two eight year old, micro-sprinkler irrigated Pinot noir grapevines on a lengthened Perold trellis during the morning and afternoon as affected by net radiation between 31 December 1994 and 2 January 1995, *i.e.* during phase III of berry development, at Stellenbosch.

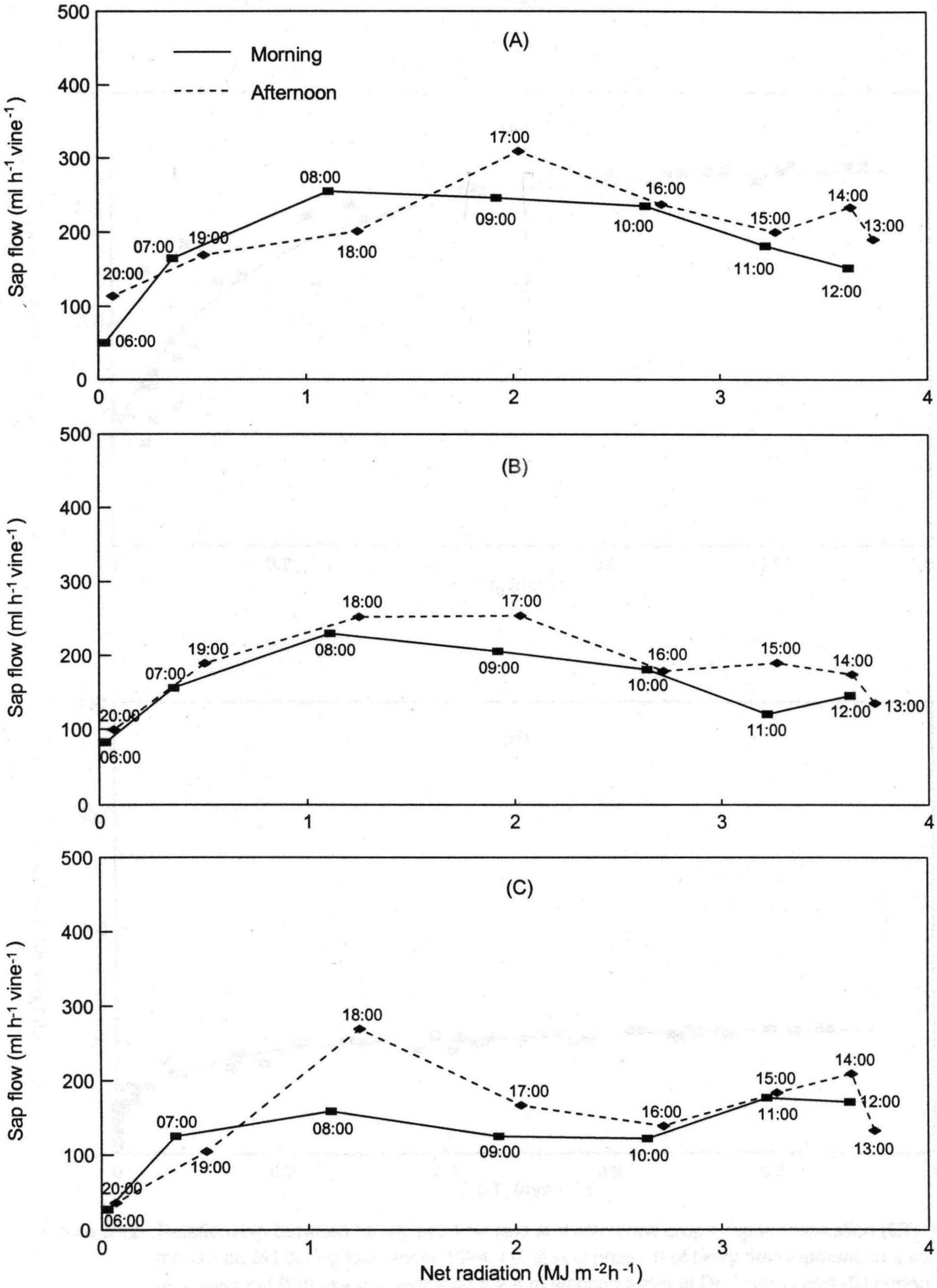


Figure 3.11. Average diurnal variation of hourly sap flow rate in three sixteen year old, flood irrigated Sultanina grapevines on a 2,4 m slanting trellis during the morning and afternoon as affected by net radiation as measured from 23 January until 26 January 1995, *i.e.* just prior to harvest at Upington. Total leaf areas of grapevines were (A) 10,25 m^2, (B) 7,60 m^2 and (C) 5,22 m^2.

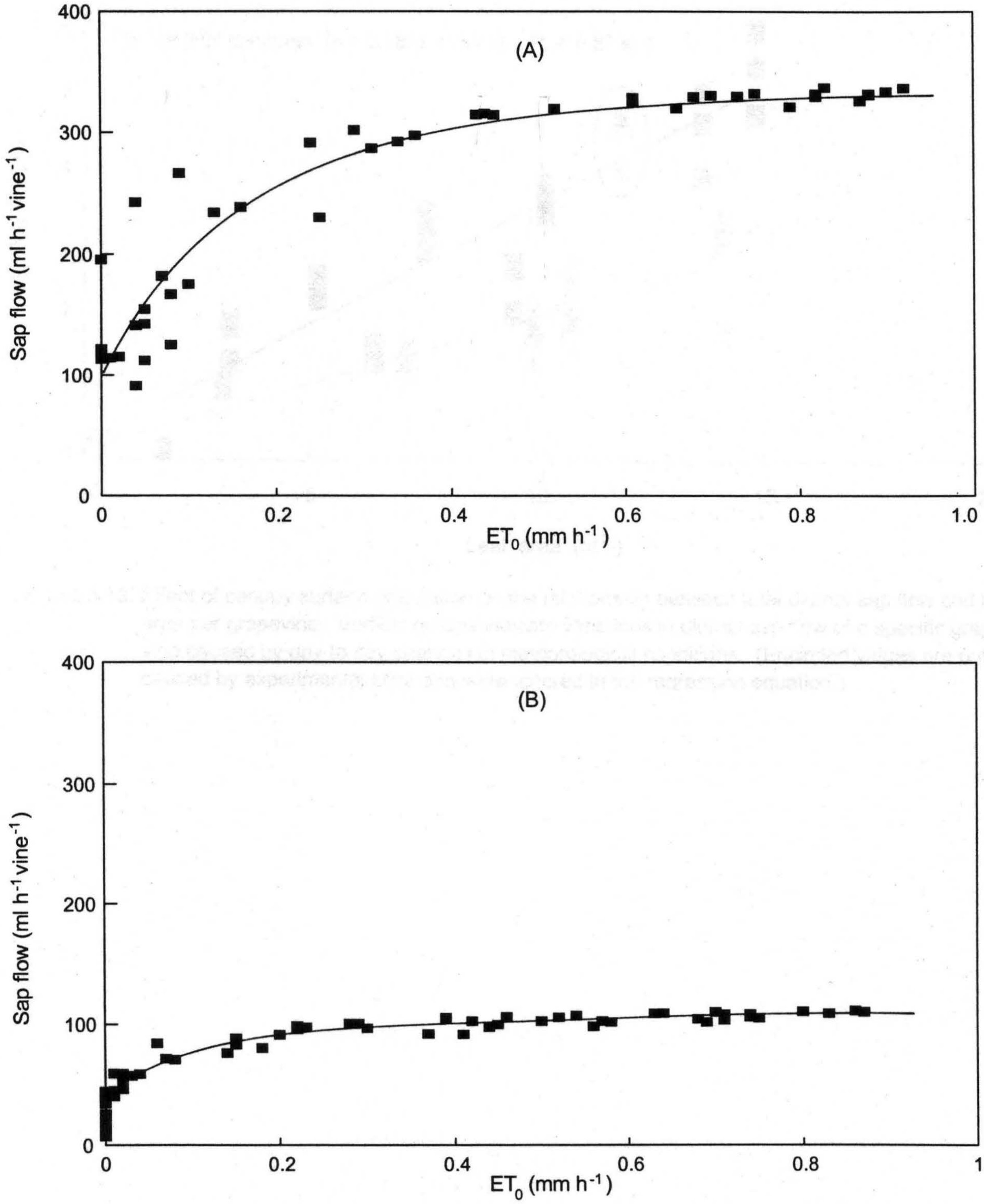


Figure 3.12. Relationship between hourly sap flow rate and reference crop evapotranspiration (ET_0) measured (A) during December 1994, *i.e.* during phase II of berry development, in a sixteen year old Barlinka grapevine on a 2,4 m slanting trellis at De Doorns and (B) during January 1995, *i.e.* during ripening, in an eight year old Pinot noir grapevine on a lengthened Perold trellis at Stellenbosch (Curves fitted by eye).

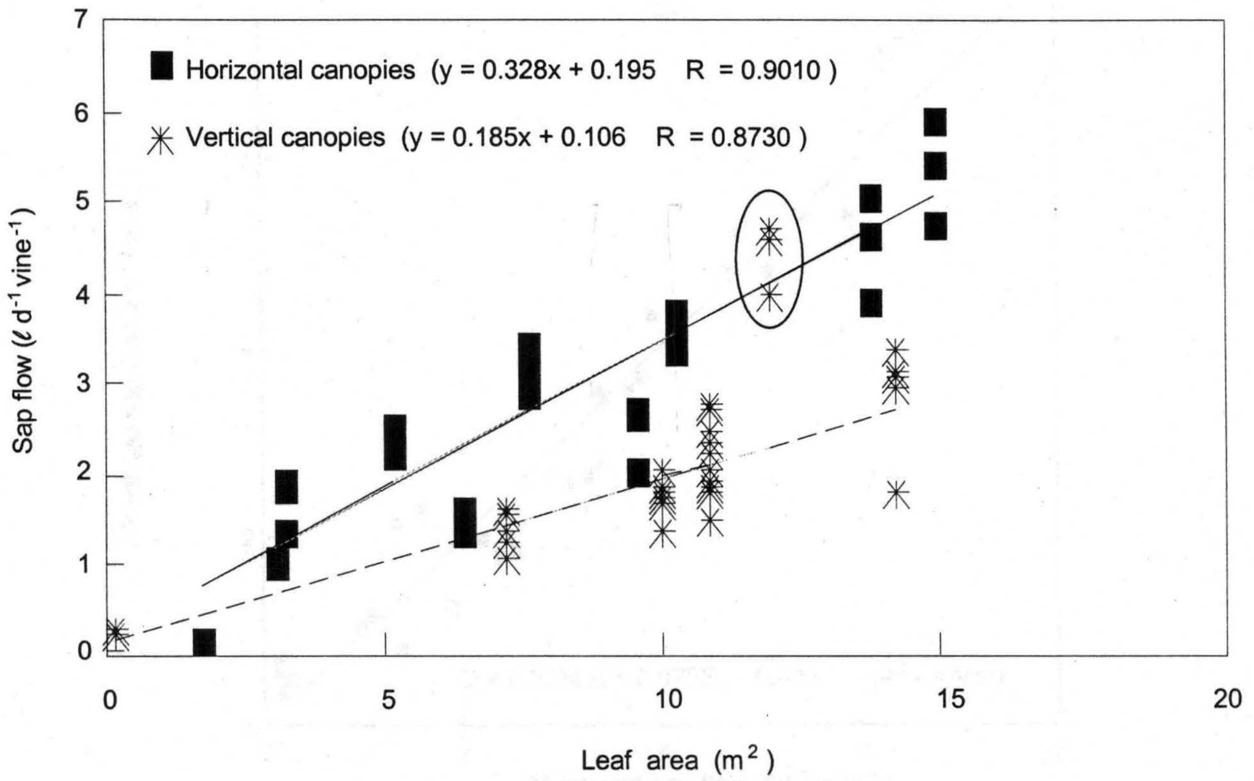


Figure 3.13. Effect of canopy surface orientation on the relationship between total diurnal sap flow and leaf area per grapevine. Vertical groups indicate variations in diurnal sap flow of a specific grapevine caused by day to day changes in meteorological conditions. (Encircled values are outliers caused by experimental error and were ignored in the regression equation.)

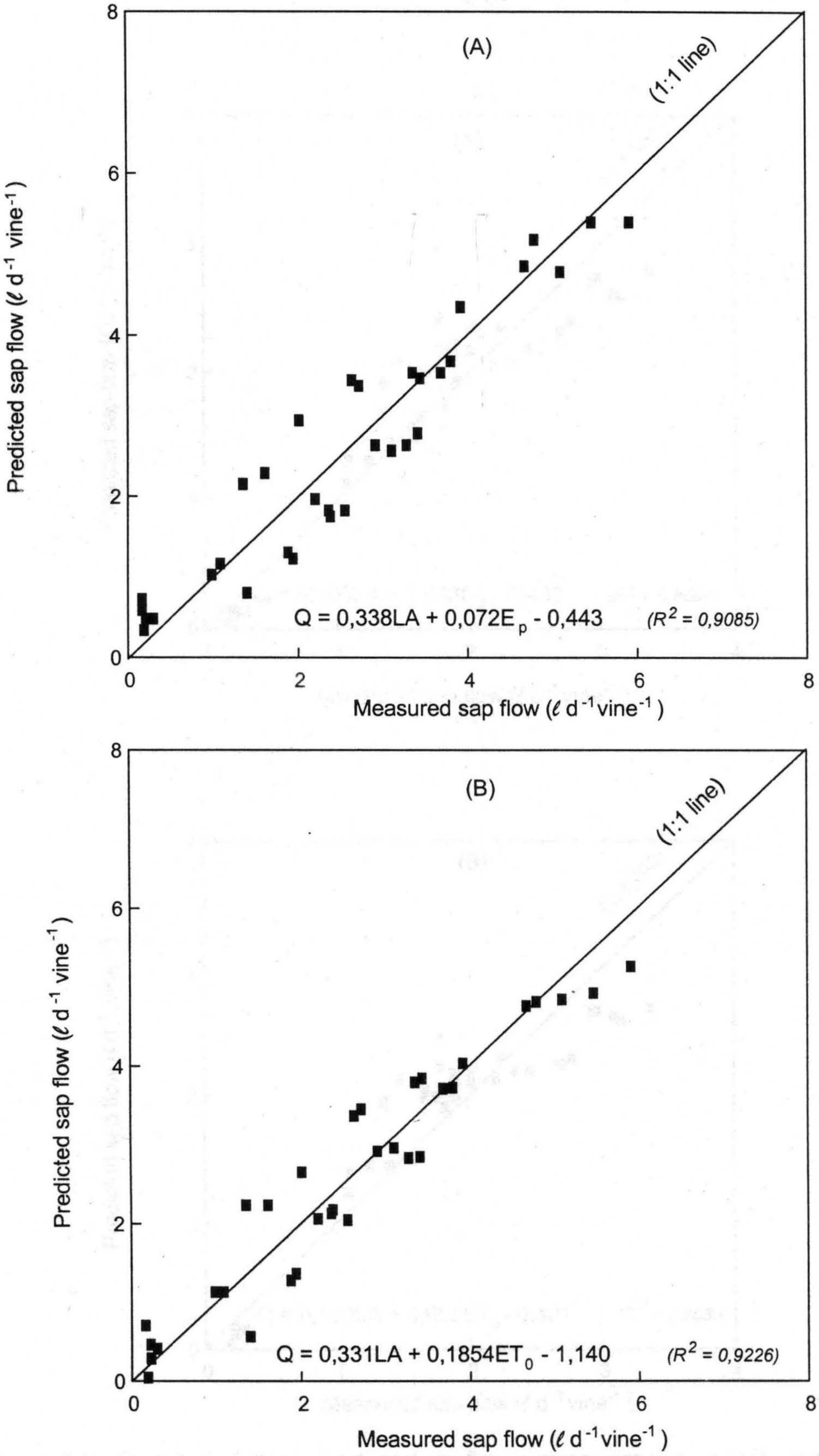


Figure 3.14. Predicted *vs* measured diurnal sap flow in grapevines with horizontally orientated canopy surfaces as obtained by multiple linear regression using (A) daily Class-A pan evaporation (E_p) and leaf area per grapevine (LA) and (B) daily reference crop evapotranspiration (ET_0) and leaf area per grapevine.

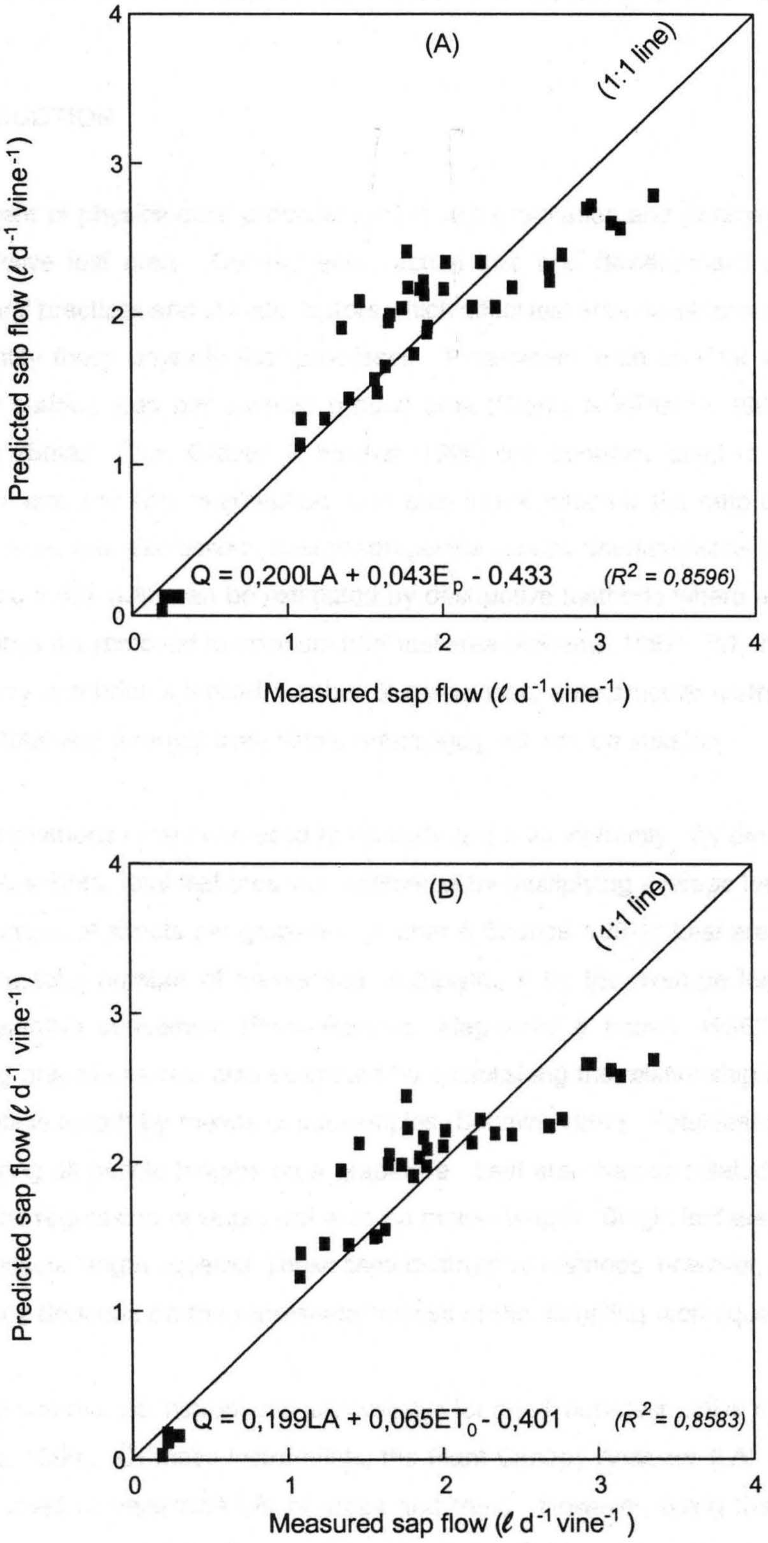


Figure 3.15. Predicted *vs* measured diurnal sap flow in grapevines with vertically orientated canopy surfaces as obtained by multiple linear regression using (A) daily Class-A pan evaporation (E_p) and leaf area per grapevine (LA) and (B) daily reference crop evapotranspiration (ET_0) and leaf area per grapevine.

CHAPTER 4

CALIBRATION OF AN INSTRUMENT FOR INDIRECT ESTIMATION OF LEAF AREA INDEX IN VINEYARDS

4.1 INTRODUCTION

The extent of physiological processes such as transpiration and photosynthesis largely depend on effective leaf area. Consequently, actual size and development of leaf area as well as viticultural practices and climatic factors which affect leaf area development should be considered to quantify these physiological processes. Parameters such as total leaf area per grapevine, canopy surface area per covered ground area (Grantz & Williams, 1993) or canopy leaf layer number (Smart, Dick, Gravett & Fischer, 1990) are generally used to characterize vegetative development and light interception. Leaf area index, which is the ratio of projected leaf area to ground area, was also used to quantify grapevine canopy characteristics (Archer & Strauss, 1991). Leaf area index (LAI) can be estimated by destructive methods where all the leaves from single grapevines are removed to measure total leaf area (Williams, 1987). When experimental treatment plots only comprise a limited number of grapevines, a destructive method where leaf sampling entails total leaf removal from single grapevines, will not be suitable.

Various methods have been used to estimate leaf area indirectly. By determining the leaf area of selected shoots, total leaf area was estimated by multiplying average leaf area per shoot by the total number of shoots per grapevine (Archer & Strauss, 1991). Leaf area was also estimated by counting total number of leaves and multiplying it by the average leaf area obtained from a representative subsample (Poni, Rebucci, Magnanini & Intrieri, 1996). Leaf area of Weisser Riesling grapevines was also estimated by establishing the relationship between single leaf area and petiole length by means of subsamples (Schmid, 1997). Total leaf area was determined by measuring all petiole lengths on a grapevine. Leaf area was calculated from petiole lengths by using the regression of single leaf area on petiole length. Single leaf area was approximately 1,6 times petiole length squared. These semi-destructive methods, however, are time consuming and accuracy depends on the representativeness of the sampling technique.

Several commercial instruments are available for rapid, non-destructive methods of estimating LAI (Welles, 1990). Of these instruments, the Plant Canopy Analyzer (LAI - 2000, Li-Cor) has been widely used to determine LAI of crops and trees. However, using the Plant Canopy Analyzer (PCA) to determine LAI of grapevine canopies in California resulted in unusually low estimates compared to actual data. Consequently, an empirically derived measurement and calculation protocol was developed for using the PCA in the specific Thompson Seedless vineyard trained onto a T-trellis. Even when the data were recalculated by using Li-Cor software options, specifically designed for this purpose, PCA measured LAI was below actual LAI until the latter reached values of approximately 5 m^2 m^{-2}. However, it was shown that the highly significant curvilinear relationship between PCA LAI and actual LAI could be used to estimate LAI accurately from data obtained by means of the PCA (Granz & Williams, 1993).

The aim of this study was to calibrate a Li-Cor LAI-2000 PCA with respect to the selected trellising systems and canopy orientations generally found in South African vineyards.

4.2 MATERIALS AND METHODS

4.2.1 The Li-Cor Plant Canopy Analyzer

The Plant Canopy Analyzer (PCA) consists of a sensor and a data logger which is easily carried and operated by one person. The PCA sensor incorporates fisheye optics to project a hemispherical image onto five concentric annular silicon ring detectors (Fig 4.1). Each of these detector rings records incoming light at different angles (Fig 4.2). To reduce the contribution of light that has been scattered by foliage, transmitted radiation is restricted to below 490 nm by means of an optical filter. Leaf area index is calculated from the difference between sky brightness recorded above the canopy and below the canopy (Welles & Norman, 1991). In both cases the lens is faced skywards. The PCA is not effective when the sky changes rapidly, *e.g.* under cloudy, windy conditions. Furthermore, to avoid direct sunlight on the lens, recordings should be made under diffuse light conditions. This is best obtained when the sun angle is low, *i.e.* at dawn or near dusk. The PCA can not distinguish between objects such as leaves, shoots, trunks and components of the trellising system. However, in relation to leaf area, the contribution of other objects to total area is relatively small and could be ignored. Also, the sensor does not distinguish between living and dead tissue. Hence, it is impossible to single out photosynthetically active LAI.

To accommodate variations in plant canopy configurations, the sensor's 360° field of view in the horizontal plane can be reduced to e.g. 270°, 180°, or 90°. Plastic delimiter caps, which fit over the lens, are provided for this purpose. Furthermore, it is possible to "mask" light recorded by specific detectors or rings by using the Li-Cor software. Data from masked rings are not used in the calculation of LAI. This option allows further adaptations to accommodate variation in canopy configurations.

4.2.2 Plant Canopy Analyzer leaf area

To obtain a range of canopy orientations and sizes, vineyards differing in cultivar, phenological phase and trellising system were selected in various grape producing regions in South Africa

(Table 4.1). Leaf area measurements were performed between two representative rows in these vineyards. Leaf area index (LAI) was measured using a Plant Canopy Analyzer (LAI-2000, Li-Cor). As recommended for row crops, a field of view (FOV) delimiter was fitted to the sensor so that only 90° of the circular lens was exposed. When recording LAI, this lens opening faced away from the operator. A leaf area index measurement consisted of one above canopy and four evenly spaced below canopy recordings which were repeated at three positions across the work row. Following the manufacturer's directions, below canopy measurements were recorded on the vine row and at 25 %, 50 % and 75 % of the distance to the adjacent row. To avoid obstructions in the field of view, a 2,0 m stepladder was used when above canopy recordings were made. During recording, the operator always faced away from the sun to avoid direct sunlight on the sensor. LAI was recorded on cloudless days during late afternoon between 17:00 and 19:00.

Since the PCA produced erratic LAI data for vertical canopies when the 90° FOV delimiter was used, the PCA calibration was extended to determine the effect of field of view on LAI measurements in vertically orientated canopies. All LAI measurements by means of the PCA were carried out as described above, except that 180° and 270° FOV delimiters were used. For this calibration, three canopy densities were obtained by (i) leaving the canopy intact and only tucking in protruding shoots, (ii) topping shoots protruding into the work row and above the trellising system and (iii) removing protruding as well as lateral shoots. These manipulations were performed during February on two adjacent rows over a distance of 15 m at each plot. Canopy density treatments were applied to Ruby Cabernet, Pinot blanc and Harslevelü in a cultivar collection vineyard at the Nietvoorbij Centre for vine and wine at Stellenbosch. These cultivars were selected on the basis of their difference in vigour under the specific conditions. Each cultivar comprised four rows. Plant spacing was 2,75 m x 1,2 m and the grapevines were trained onto a five-strand hedge (Booysen, Steenkamp & Archer, 1992). PCA measurements were carried out on all experimental plots during March after grapes were harvested. Similar canopy manipulations and PCA measurements were also repeated during March (after harvest) in a Ruby Cabernet vineyard on the ARC-Infruitec/Nietvoorbij Experimental Station near Lutzville. In this case, plant spacing was also 2,75 m x 1,2 m and the grapevines were trained onto a lengthened Perold trellis.

4.2.3 Actual leaf area

Leaf area was determined manually on all plots where the PCA was used. A grapevine with a representative canopy was selected on each plot and all the leaves were sampled on the morning after PCA measurements were made. Total one-sided leaf area was determined by means of an electronic leaf area meter (Li 3100, Li-Cor). LAI was obtained by dividing measured total leaf area (m^2) by ground area occupied per grapevine (m^2).

4.2.4 Variation in Plant Canopy Analyzer recordings during the afternoon

The variation in PCA recordings during the course of the afternoon was also investigated. For this purpose, a series of LAI recordings were made at 1 hour intervals from 14:00 until 19:00 (sunset). Measurements were performed at the ARC-Nietvoorbij Centre for Vine and Wine on 26 February 1996 in a Chenin blanc vineyard trained onto a lengthened Perold trellis as well as on 5 March 1996 in a Chenin blanc vineyard trained onto a 1,5 m slanting trellis (Zeeman, 1981). Care was taken to repeat hourly measurements at the same site in each vineyard.

4.2.5 Statistical analysis

STATGRAPHICS was used for curve fitting.

4.3 RESULTS AND DISCUSSION

4.3.1 Plant Canopy Analyzer LAI *vs* actual LAI

Similar to earlier findings (Grantz & Williams, 1993), leaf area index obtained by means of the Plant Canopy Analyzer (LAI_{pca}) was considerably lower than actual LAI. This deviation was due to the row structure of vineyards which caused relatively large gaps in the canopies. Hence, LAI_{pca} was recalculated using the Li-Cor software to "mask" various combinations of outer rings. Although masking increased LAI_{pca} values, they were still well below actual LAI (Fig. 4.3 & 4.4). When masking rings three, four and five, LAI_{pca} values were also lower than the values reported by Grantz & Williams (1993). The above-mentioned procedures were fairly similar to the protocol followed by Grantz & Williams (1993). Hence, there is no clear explanation for the lower LAI_{pca} values obtained in this study. The only reason might have been a difference between the two PCA sensors. If this was the case, each PCA would have to be calibrated individually for estimating LAI in grapevine canopies. However, by taking simultaneous readings it would be possible to calibrate a PCA sensor against an already calibrated sensor. This would eliminate the time consuming and destructive determination of actual LAI.

In this study, LAI_{pca} of horizontal canopies correlated best with actual LAI when the two outermost radiation sensor rings (four and five) were ignored in calculation of LAI (Fig. 4.3). The relationship between LAI_{pca} and actual LAI was curvilinear and by relating the square root of LAI_{pca} to actual LAI, the following regression equation was obtained :

$$(LAI_{pca})^{0,5} = 0,204\ LAI + 0,464 \qquad (R^2 = 0,9740) \qquad (4.1)$$

To convert LAI_{pca} recordings to actual LAI, equation 4.1 was inverted as follows :

$$LAI_H = [(LAI_{pca})^{0,5} - 0,464] \, / \, 0,204 \tag{4.2}$$

The standard error of estimation of LAI for horizontal canopies was ± 0,14 m m^{-1}. Hence, for a relatively wide plant spacing of 3,0 m x 2,0 m, *e.g.* for table grapes, the leaf area could be over- or underestimated by 0,84 m^2 per grapevine. If the total leaf area is 24 m^2 per grapevine the error would be ± 3,5 %.

In contrast to the horizontal canopies, using the 90° FOV delimiter in the case of vertical canopies resulted in erratic LAI estimations (data not shown). However, the relation between actual LAI and LAI_{pca} improved when the 180° FOV delimiter was used. Using the 270° FOV delimiter neither increased LAI_{pca} values, nor improved the relation between LAI_{pca} and actual LAI. Best correlation results were obtained when only ring five was masked. LAI_{pca} was also curvilinearly related to actual LAI (Fig. 4.4). However, in contrast to horizontal canopies this relation was best described by the following natural logarithmic equation :

$$LAI_{pca} = 0,3192 \ln LAI + 0,6060 \qquad (R^2 = 0,9855) \tag{4.3}$$

To convert LAI_{pca} measurements to actual LAI, equation 4.3 was inverted as follows :

$$LAI_V = \exp\,(3,132\ LAI_{pca} - 1,898) \tag{4.4}$$

The standard error of estimation of LAI for vertical canopies was ± 0,09 m m^{-1}. For a 2,75 m x 1,5 m plant spacing, typically used for wine grape vineyards, leaf area would be over- or underestimated by ± 0,37 m^2 per grapevine. Hence, for a total leaf area of 10 m^2 per grapevine the error would amount to ± 3,7%.

According to Welles & Norman (1991) sunlit leaves in the canopy would increase the amount of diffuse radiation, causing a decrease in PCA leaf area index. In the case of vertical grapevine canopies an appreciable amount of diffuse radiation can be reflected into the inter row space and consequently, onto the sensor. In fact, the vertical side of the canopy could act as a reflector. Hence, the amount of reflected radiation would probably increase as canopy density and LAI increase. This could be a possible explanation for the continued departure of LAI_{pca} from the 1:1 line at higher actual LAI values in the case of vertical canopies. However, shading large areas in vineyards to overcome this problem, would be impractical. Furthermore, time limited diffuse light conditions at dawn or near dusk would not allow the large number of measurements sometimes required for comparative studies.

4.3.2 Variation in Plant Canopy Analyzer recordings during the afternoon

Hourly values of LAI_{pca} remained fairly constant during the course of the afternoon. Only a slight increase was observed at 19:00 (near sunset). For the horizontal canopy, LAI_{pca} varied within acceptable limits between 15:00 and 19:00 (Fig. 4.5A), whereas least variation occurred between 14:00 and 18:00 in the case of the vertical canopy (Fig. 4.5B). This suggested that the PCA was relatively insensitive to sun angle under the prevailing conditions. During mid season (December to January) higher sun angles during the early afternoon might have caused more pronounced deviations in LAI_{pca}. These results, however, indicate that it would be possible to measure LAI by means of the PCA on a sufficient number of experimental plots during one afternoon if this parameter was to be assessed in a comparative study.

Due to easy handling and short recording times, it took approximately three minutes to complete a LAI_{pca} recording on an experimental plot. Maximum time lapse between a below canopy and the nearest above canopy reading was *ca* 40 seconds. This was relatively quick in comparison to the five minutes reported in a study where the PCA was used to estimate LAI in a walnut orchard (Martens, Ustin & Rousseau, 1993).

4.4 CONCLUSIONS

The Li-Cor PCA underestimated actual leaf area index. Decreasing the field of view in combination with the use of software options could not increase values of LAI estimations. However, close correlation between LAI_{pca} and actual LAI indicated that the PCA could be used for estimation of leaf area index. Consequently, an empirical calibration approach was followed to convert LAI_{pca} to actual LAI. Using a 90 ° FOV delimiter and masking the two outermost rings allowed the most acceptable calibration curve for a range of various horizontal canopies. In the case of vertical canopies, the best calibration curve was obtained by using a 180 ° FOV delimiter and masking only the outermost ring. When using the calibration curves, the error of estimation of leaf area per grapevine was less than 5 % for typical grapevine canopies. Due to possible variation among individual sensors, the calibration curve for horizontal trellising systems obtained in this study was not similar to earlier findings. This problem, however, can be overcome by calibrating a PCA against an already calibrated instrument. Stability of the PCA offers the opportunity to complete a series of rapid readings during the course of an afternoon. This feature would allow the estimation of LAI on a large number of experimental plots generally required in field studies.

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TABLE 4.1

Locality, trellising system, cultivar and phenological stage of vineyards used in the calibration of a Li-Cor LAI-2000 Plant Canopy Analyser for measuring leaf area index in vineyards.

Locality	Trellising system *	Cultivar	Phenological stage **
Stellenbosch	1,5 m Slanting trellis	Chenin blanc	1, 2, 3, 4, 5, 6
	Lengthened Perold	Chenin blanc	1, 2, 3, 4, 5, 6
	Lengthened Perold	Pinot noir	1, 2, 4
Robertson	5-Strand hedge	Emerald Riesling	3, 4, 5, 6
De Doorns	2,4 m Slanting trellis	Barlinka	1, 2, 3, 4, 5
Lutzville	Factory trellis	Colombar	4, 5
	Lengthened Perold	Ruby Cabernet	4, 5
Upington	2,4 m Slanting trellis	Sultanina	1, 2, 3, 4, 5, 6
	Gable trellis	Sultanina	1, 2, 3, 4, 5, 6
	2,4 m Slanting trellis	Chenel	2
	Factory trellis	Chenel	2
	T-trellis	Chenel	2
	5-Strand hedge	Chenel	2

* Trellising systems used in this study to obtain different canopy surface orientations and sizes.

** 1 = 100 mm Shoot length; 2 = Flowering (80 % cap fall); 3 = Fruit set (7 days after cap fall); 4 = Pea size berries; 5 = Véraison (50 % berries showed discoloring); 6 = Ripening.

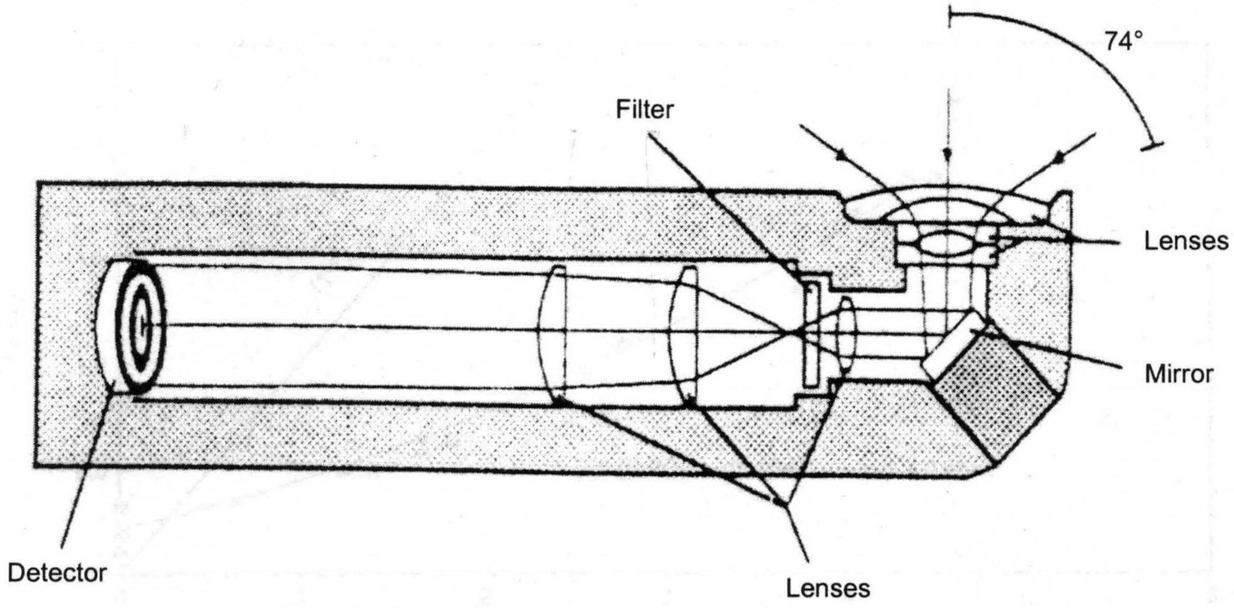


Figure 4.1. Schematic diagram of LAI-2000 Plant Canopy Analyzer sensor head used to determine leaf area index in vineyards (Welles & Norman, 1991).

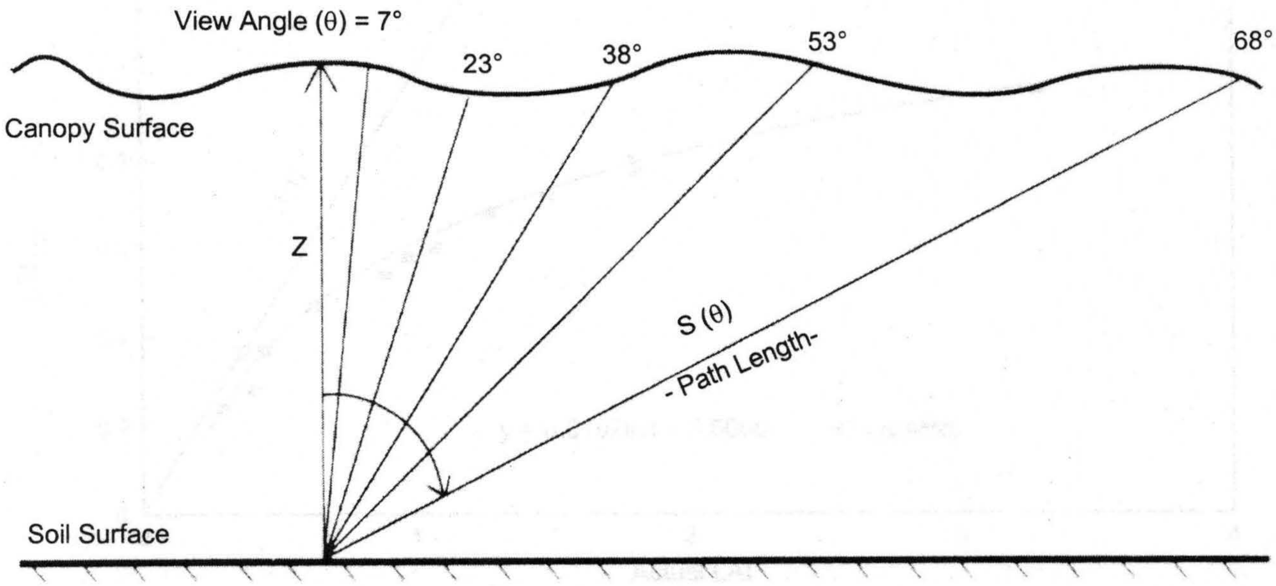


Figure 4.2. Angular bands at which diffuse radiation was measured by means of the LAI-2000 Plant Canopy Analyzer (LI-COR, 1991).

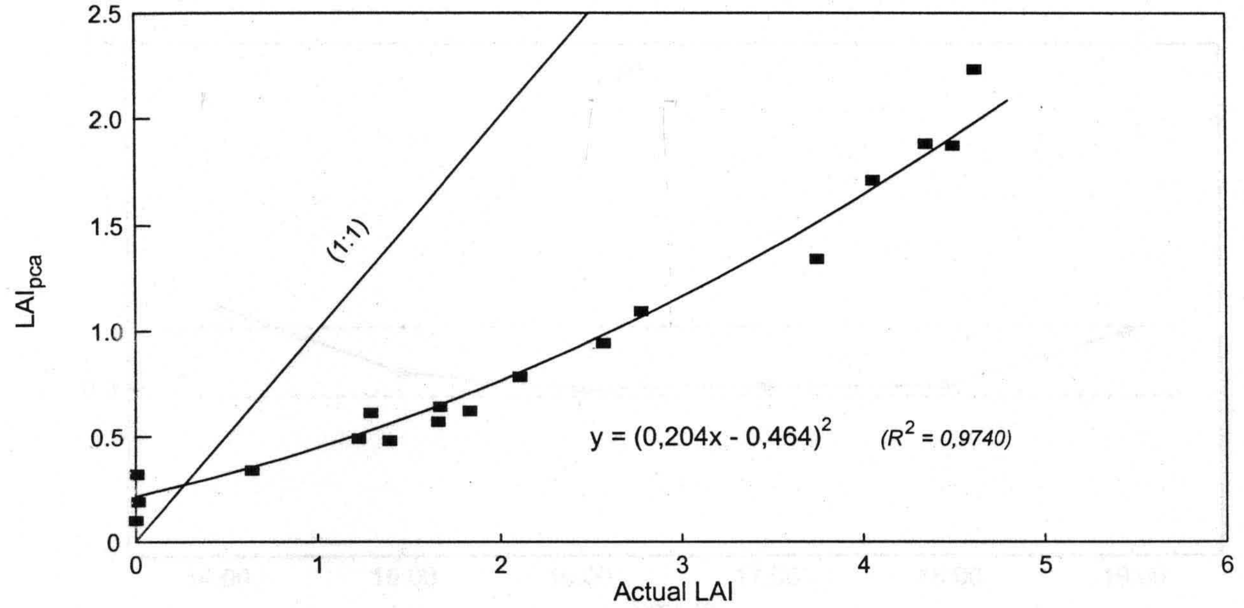


Figure 4.3. Relationship between LAI-2000 Plant Canopy Analyzer recordings (LAI_{pca}) and actual leaf area index as determined for horizontal grapevine canopies at different localities.

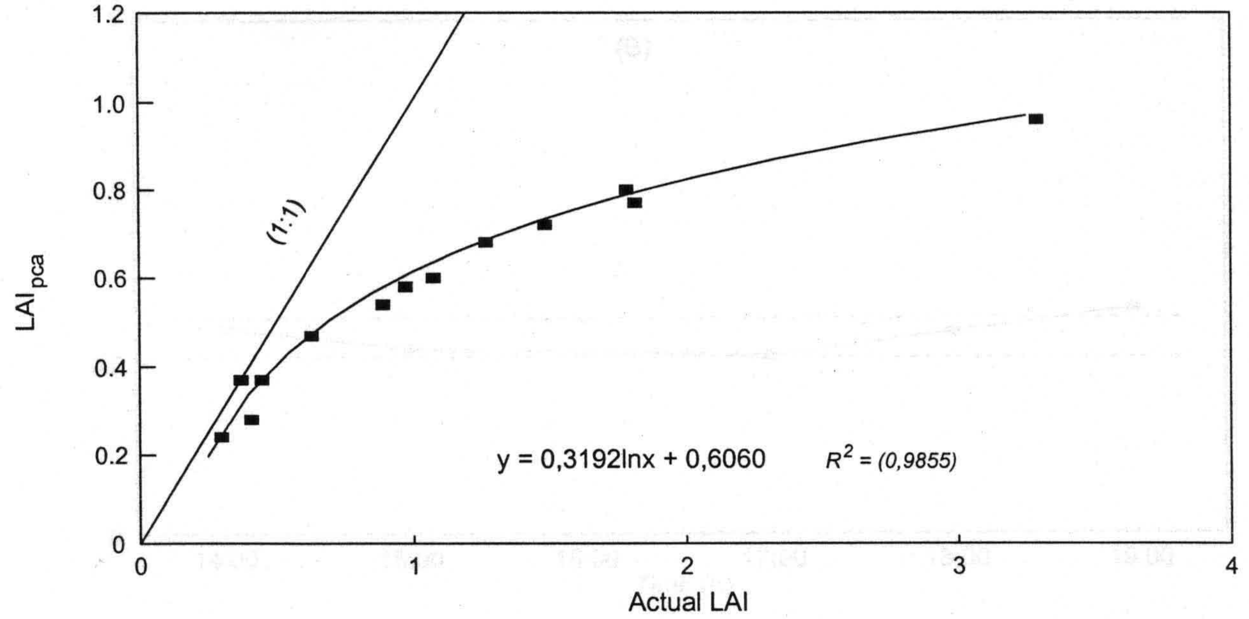
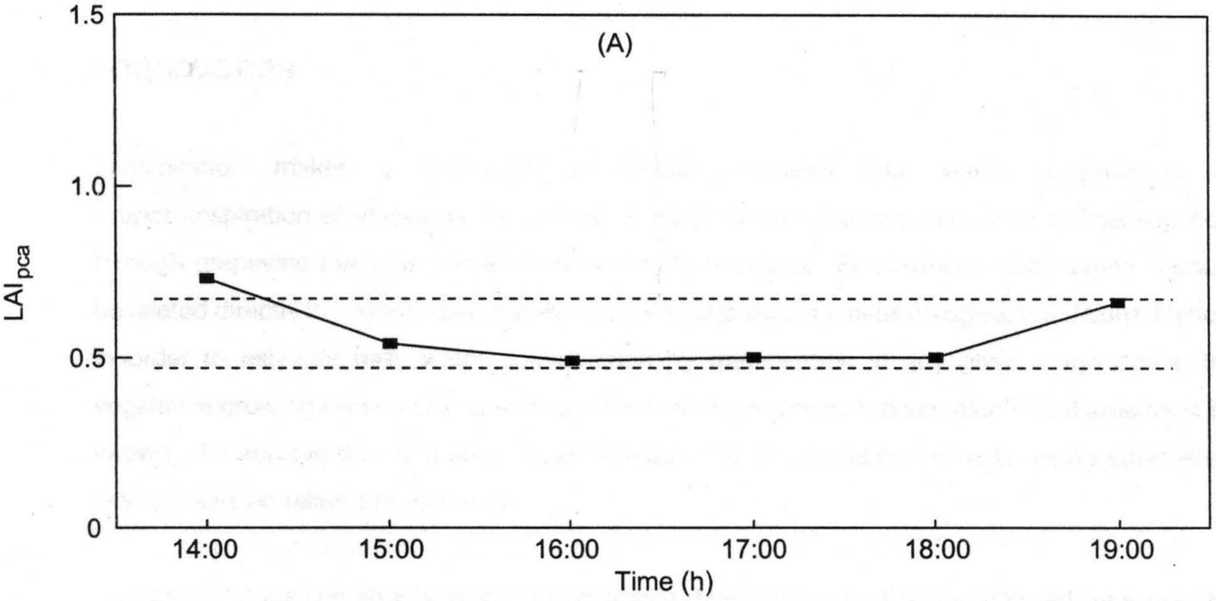


Figure 4.4. Relationship between LAI-2000 Plant Canopy Analyzer recordings (LAI_{pca}) and actual leaf area index as determined for vertical grapevine canopies at different localities.



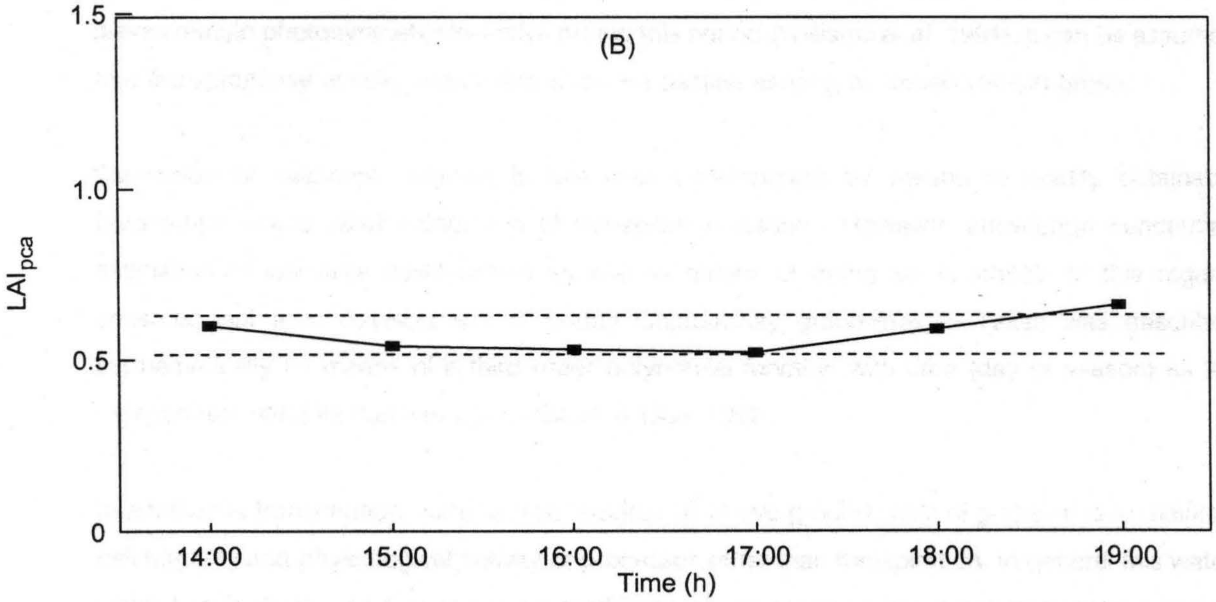


Figure 4.5. Variation in Plant Canopy Analyzer recordings as measured during March 1996, *i.e.* after harvest, at Stellenbosch in (A) a Chenin blanc vineyard on a slanting trellis using the 90° field of view delimeter and (B) a Chenin blanc vineyard on a vertical trellis using the 180° field of view delimeter. (Dashed horizontal lines indicate ± one standard deviation from the mean).

CHAPTER 5

ESTIMATING LEAF AREA DEVELOPMENT AND SEASONAL VARIATION IN WATER CONTENT OF ABOVE-GROUND GROWTH OF SELECTED SOUTH AFRICAN VINEYARDS

5.1 INTRODUCTION

Transpiration makes a substantial contribution towards total water consumption or evapotranspiration of vineyards. In Chapter 3 it was shown that the amount of diurnal sap flow through grapevine trunks is primarily caused by transpiration. Furthermore, daily sap flow could be related directly to leaf area per grapevine as well as prevailing meteorological conditions. Hence, in order to estimate daily water consumption by transpiration at any given stage during the vegetative growing season of grapevines, seasonal development and variation in leaf area must be known. To achieve this, leaf area could be measured or calculated indirectly using parameters which could be related to leaf area.

In general, grapevine shoots initially grow slower directly after bud break followed by a massive growth of vegetative tissues during late spring which has been termed the "grand period of growth" (Coombe, 1992). Shoot lengthening slows during mid-summer until shoot tip abscission sets in. Vegetative growth commonly continues until véraison (Williams *et al*, 1994). It is uncertain whether transpiration activity would decline as leaf area declines from harvest until leaf fall. However, since leaves remain photosynthetically active during this period (Williams *et al*, 1994), it can be assumed that transpirational activity would also show no decline as long as leaves remain green.

Estimation of seasonal variation in leaf area development by means of readily obtainable parameters would allow calculation of transpiration losses. However, knowledge concerning estimation of leaf area development as well as means of doing so, is limited. In this regard, seasonal leaf area development of young Chardonnay grapevines in Texas was described mathematically by means of a third order polynomial function with time (day of season) as the independent variable (Lascano, Baumhardt & Lipe, 1992).

In addition to transpiration, water is also required by above-ground parts of grapevines to maintain cell turgidity and physiological activity of processes other than transpiration. In general this water, which is actually the amount of water stored in the above-ground parts, amounts to approximately 6 millimetres during the growing season (Smart & Coombe, 1983). This amount of water appears to be insignificant in comparison to total seasonal water consumption, *i.e.* transpiration plus evaporation from the soil surface, which was estimated to vary between 286 mm and 860 mm under South African conditions (Van Zyl, 1981) and between 250 mm and 800 mm under Australian conditions (McCarthy, Jones & Due, 1992).

The aims of this study were: (i) to measure total leaf area development in a number of vineyards in various grape growing regions, (ii) to develop a model to calculate actual leaf area development by means of readily obtainable parameters, and (iii) to quantify the amount of water required for seasonal growth and maintaining cell turgidity and physiological activities other than transpiration.

5.2 MATERIALS AND METHODS

5.2.1 Experimental vineyards

For the purpose of this study, a number of vineyards varying in cultivar, vine spacing and trellising system were selected in five grape growing regions (Table 5.1). These vineyards represented cultivars, trellising systems and climatic conditions commonly found in South Africa. Except for one, all vineyards were situated on experimental stations of the ARC-Infruitec/Nietvoorbij Fruit, Vine and Wine Institute. During this study, vineyards were managed as production units. Hence, standard recommended viticultural practices as well as irrigation and pest control management were followed. In particular it must be noted that irrigation management was such that water stress should not have occurred.

5.2.2 Leaf area index

Leaf area index was measured once a month by means of a Plant Canopy Analyzer (LAI-2000, Li-Cor). Measurements were performed according to the method described in Chapter 4. Calibration curves, *i.e.* equations 4.2 or 4.4, were used to convert Plant Canopy Analyzer leaf area index (LAI_{pca}) to actual leaf area index (LAI). Monthly measurements, which commenced approximately two weeks after budbreak, were repeated at the same site in a specific vineyard. Measurements were terminated after harvest when leaves began to change colour.

To allow comparison between leaf area development of various vineyards, LAI was normalized by calculating relative leaf area index (LAI') as follows :

$$LAI' = LAI/LAI_X \qquad (5.1)$$

where LAI is leaf area index on a given day and LAI_X is maximum leaf area index measured during the growing season. LAI' was plotted against day of season (DOS) where budbreak was taken as day one. Second and third order polynomial equations were fitted to LAI' versus DOS plots for each vineyard.

Actual leaf area per vine (LA) in m^2 was obtained by multiplying LAI with the vine spacing of the specific vineyard as follows:

$$LA = LAI \times W_P \times W_R \qquad (5.2)$$

where W_P is the distance (m) between grapevines in the row and W_R is the distance (m) between rows.

5.2.3 **Leaf, shoot and bunch water content**

On the morning after LAI measurements, leaves, shoots and, where applicable, bunches were removed from a single representative grapevine. The various organs were immediately placed in plastic bags to minimize water losses. Fresh weight was obtained by weighing as soon as possible after removal. After drying at 60°C until constant mass (kg) was attained, organs were weighed again to obtain dry mass (kg). Water content fraction of an organ (Θ) was calculated as follows:

$$\Theta = (\text{Fresh mass - Dry mass}) \, / \, \text{Fresh mass} \qquad (5.3)$$

Calculating Θ for each organ, and assuming a plant water density of 1 Mg m^{-3}, total canopy and bunch water content was calculated as follows:

$$WC_T = [(M_L \times \Theta_L) + (M_S \times \Theta_S) + (M_B \times \Theta_B)] \, / \, (W_P \times W_R) \qquad (5.4)$$

where

WC_T = Total water content of canopy and bunches (mm)

Θ_L = Water content fraction of leaves

Θ_S = Water content fraction of shoots

Θ_B = Water content fraction of bunches

M_L = Fresh mass of leaves per grapevine (kg)

M_S = Fresh mass of shoots per grapevine (kg)

M_B = Fresh mass of bunches per grapevine (kg)

W_P = Distance between grapevines (m)

W_R = Distance between rows (m)

Since a plant water density of 1 Mg m^{-3} was assumed, the mass of water could be expressed in terms of volume (ℓ). Hence, WC_T could be expressed in mm (litres / square meters = mm).

During determining fresh mass of leaves shoots and bunches, a time lapse generally occurred between sampling and weighing. The extent of possible errors due to weight loss during transportation and handling was determined as follows: On 20 December 1995 all leaves from a single shoot were removed from a Ruby Cabernet grapevine trained onto a five strand lengthened Perold at the ARC-Infruitec/Nietvoorbij Lutzville Experimental Station. Leaves were immediately placed in a plastic bag and sealed. After leaf removal, all bunches were removed and sealed in plastic bags. Shoots were then removed, cut to 150 mm lengths and also sealed in plastic bags. These procedures were repeated five times with leaves from representative shoots on different grapevines.

Samples were transported to the laboratory and weighed. After the first weighing, samples, were left in the bags and weighed again after five minutes. Samples were then removed, placed on the plastic bags and weighed after 10, 30 60, 90 and 120 minutes. After drying at 60 °C until constant mass was attained, samples were weighed to obtain dry mass. Water content was calculated by means of equation (5.2).

5.2.4 Cane mass

Cane mass was determined when the eight experimental vineyards were pruned after leaf fall during winter (Table 1). For this purpose, mean cane mass of five vines was determined at sites where LAI measurements were carried out during the growing season. To extend this data base, data for maximum leaf area *vs* cane mass at pruning were obtained from the following studies : (i) An irrigation field trial with Barlinka at De Doorns (Myburgh, 1996), (ii) An irrigation field trial with Sultanina at Upington (Myburgh, unpublished data) (iii) experimental plots used in the calibration of the LiCor PCA for vertical canopies at Stellenbosch as reported in Chapter 4, and (iv) a vine spacing field trial with Pinot noir at Stellenbosch (Archer & Strauss, 1991). The linear regression of maximum leaf area (LA_x) on average cane mass per grapevine was determined.

5.2.5 Statistical analyses

Regression analyses were performed to investigate possible significant trends in leaf area development over time. Best fit was obtained with third order polynomial functions of time (day of season). Slopes and intercepts of regression lines were subsequently compared using Student's *t*-LSD ($P=0,05$)(Snedecor & Cochran, 1982). In instances where significant differences were not found, data were combined. SAS was used for these analyses. STATGRAPHICS was used for linear regression analyses.

5.3 RESULTS AND DISCUSSION

5.3.1 Actual leaf area

Actual seasonal leaf area development of the eight vineyards are presented in Fig. 5.1. Depending on the climatic conditions and cultivar, maximum leaf area was generally obtained between December and February. Maximum leaf area varied between *ca* 8 m^2 per vine for Emerald Riesling on a vertical trellis at Robertson (Fig. 5.1D) and 39 m^2 for Barlinka on a slanting trellis at De Doorns (Fig. 5.1C). This suggested that the variation in transpiration losses between vineyards could be almost as high as 500 % depending on leaf area. Furthermore, depending on the effects of climate and cultivar on bud break, leaf area development started at various times.

5.3.2 Estimating normalized leaf area index

Variation in normalized leaf area index (LAI') as a function of day of season (DOS) for the various vineyards are presented in Figure 5.2. When using third order polynomial equations to predict seasonal variation in LAI', higher R^2 values were obtained compared to second order polynomials. Statistical analysis revealed that coefficients for DOS, DOS^2, DOS^3 as well as the intercepts did not differ significantly among most of the vineyards monitored in this study. The only exceptions were the two Sultanina vineyards at Upington (Fig 5.3). Warmer climatic conditions in the latter area generally prolonged vegetative growth to such an extent that leaf fall occurred significantly later in the season compared to vineyards in the cooler climatic conditions of the Western Cape areas. The third order polynomial equation which described the seasonal variation of normalized leaf area index for the Winter Rainfall Region (LAI'_W) best after data were combined, was as follows :

$$LAI'_W = 0{,}00569\ DOS + 6{,}7\ E - 05\ DOS^2 - 3{,}84\ E - 07\ DOS^3 - 0{,}047 \qquad (R^2 = 0{,}9175) \qquad (5.5)$$

For the Summer Rainfall Region variation in normalized leafarea index (LAI'_S) could be described by the following polynomial equation :

$$LAI'_S = 0{,}00666\ DOS + 2{,}3\ E - 05\ DOS^2 - 1{,}48\ E - 07\ DOS^3 - 0{,}027 \qquad (R^2 = 0{,}9664) \qquad (5.6)$$

In equations (5.6) and (5.7) LAI' is normalized leaf area index and DOS is day of season where bud break was taken as day one. For the purpose of this study, these equations will be referred to as potential growth curves. Since these growth curves were developed for irrigated vineyards where no or little water stress occurred, their application would be limited to vineyards under similar conditions. Furthermore, application of these curves would also be limited to the regions where the data were obtained. Expressing leaf area development as a function of cumulative heat units instead of time might be a solution to the problem of variation in potential growth curves between seasons. This approach, however, was beyond the scope of this study and should be adressed by further research.

5.3.3 **Maximum leaf area index *vs* cane mass**

The relationship between cane mass at pruning and maximum leaf area (LA_X) is shown in Figure 5.4. There was a distinct difference in this relationship between horizontal and vertical canopies. Vertical canopies clearly produced less leaves per unit cane mass compared to horizontal canopies. The relatively poor correlation was probably due to cultivar differences and variations in shoot water content at pruning. Relating maximum leaf area to oven dried cane mass would probably have improved the prediction of leaf area. Variation in maximum leaf area with cane mass for horizontal canopies (LA_{xH}) could be explained by means of the following linear regression equation:

$$LA_{xH} = 13{,}66\ M_p + 6{,}17 \qquad (R^2 = 0{,}7532;\ n = 17)) \qquad (5.7)$$

where M_p is cane mass (kg vine^{-1}). The standard error of leaf area estimation was ± 0,46 m^2 per grapevine. For vertical canopies the regression equation was as follows:

$$LA_{xV} = 7{,}81\ M_p - 0{,}23 \qquad (R^2 = 0{,}7746;\ n = 17) \qquad (5.8)$$

where LA_{xV} is leaf area per grapevine. In this case the standard error of leaf area estimation was ± 0,32 m^2 per grapevine.

5.3.4 **Leaf area *vs* leaf fresh mass**

Total leaf area per vine was closely related to leaf fresh mass at any stage during the growing season (Fig. 5.5). This relationship was not affected by cultivar or trellis orientation. Variation in leaf area with leaf fresh mass could be explained by means of the following linear regression equation :

$$LA = 5{,}001\ M_L - 0{,}18 \qquad (R^2 = 0{,}9936) \qquad (5.9)$$

where LA is leaf area per grapevine (m^2) and M_L is leaf fresh mass (kg).

When the slope of the regression of leaf area on leaf mass (Equation 5.9) was inverted, fresh mass per unit leaf area, or specific leaf mass, amounted to 20 mg cm^{-2}. Comparable specific leaf mass values were obtained for Cabernet Sauvignon grapevines (Hunter & Visser, 1989). These results suggested that leaf area could be calculated from leaf mass with a standard error of estimation of ± 0,07 m^2 per grapevine. However, leaf mass should be determined directly after removal from the grapevine. This can be accomplished by using a portable battery-operated electronic balance in the vineyard.

5.3.5 Estimating seasonal leaf area development

Leaf fresh mass

The following procedure was used to estimate actual leaf area development by means of leaf fresh mass and day of season as the only input parameters :

(i) Using equation (5.10), leaf area on a given day of season (LA_n) was calculated from the leaf fresh mass as measured on that specific day.

(ii) Leaf area index on day n (LAI_n) was derived from equation 5.2 as follows :

$$LAI_n = LA_n / (W_P \times W_R) \qquad (5.10)$$

where W_P is distance between grapevines in the row and W_R is the distance between rows.

(iii) By distinguishing between winter and summer rainfall climate, either equation 5.6 or 5.7 was used to calculate normalized leaf area index on that specific day (LAI'_n).

(iv) By rewriting equation 5.1, LAI_x was calculated using LAI_n and LAI'_n.

(v) Using equation 5.6 or 5.7 for Winter or Summer Rainfall Regions, respectively, LAI' was calculated for each day of the season following bud break.

(vi) Daily LAI' values were then converted to actual LAI by rewriting equation 5.1.

(vii) Finally, actual daily leaf area was calculated from daily LAI values using equation 5.11.

Cane mass

The following procedure is proposed to estimate seasonal leaf area development by means of cane mass and day of season: First, LA_x is calculated by means of equation 5.8 or 5.9 for horizontal and vertical canopy orientation, respectively. LAI_x is obtained by dividing by the area allocated per grapevine as shown in equation 5.11. Steps (v) to (vii) are then followed to calculate actual daily leaf area development as described above.

5.3.6 Experimental errors during sampling and weighing

Shoot and bunch water content only decreased by less than 2 % during the two hour period after sampling (Fig. 5.6). Since samples were normally removed and weighed within one hour, experimental errors could be ignored in the case of shoots and bunches. Water content of leaves, however, decreased by *ca* 10 % over the two hour period. This indicated that a considerable amount of water was lost by continued transpiration and that errors of up to 7 % could have occurred in determining the water content of leaves if they were not weighed within an hour. Warm climatic conditions and storing leaves in full sunshine would have increased this error beyond the values obtained in this study.

5.3.7 Seasonal variation in leaf, shoot and bunch water content

Due to errors which occurred during weighing at Lutzville, water content data obtained for this locality were ignored. Water content of leaves tended to decrease from flowering until ripening in vineyards where leaf area was determined (Fig. 5.7A). These results are, to some extent, in agreement with the reduction of leaf water content from *ca* 73 % at berry set to *ca* 63 % at ripeness measured in Cabernet Sauvignon grapevines (Hunter & Visser, 1990). In general, leaf water content did not vary between vineyards at different localities at any stage during the season. The outlier values were probably the result of the susceptibility of leaf water content to experimental errors during weighing as explained above.

In contrast to leaves, water content in shoots decreased approximately by 15 % as the season progressed (Fig. 5.7B). This tendency occurred irrespective of cultivar or locality. Increasing woodiness probably caused the decreasing tendency in shoot water content. Bunch water content also showed relatively limited variation between vineyards differing in cultivar and locality (Fig. 5.7C). Maximum bunch water content was obtained near the end of the berry development stage. During ripening, bunch water content tended to decrease slightly.

5.3.8 Total water content of canopies and bunches

Total seasonal water content of vegetative growth, including bunches, varied between 2 mm and 7 mm for the vineyards used in this study (Fig. 5.8). The maximum amount of water measured was in agreement with the average value of 6 millimetres reported by Smart & Coombe (1983). During the seven months growing period, the average daily water extraction would only amount to a fraction of a millimetre. Hence, the amount of water needed to maintain cell structure as well as physiological processes other than transpiration, constituted an insignificant fraction of daily vineyard evapotranspiration.

5.4 CONCLUSIONS

Due to variations in cultivar and climate conditions, actual leaf area as well as the onset of leaf area development varied substantially between the eight vineyards monitored in this study. For the winter rainfall region the potential growth curves, however, tended to be fairly similar, irrespective of cultivar, viticultural or meteorological conditions. Potential growth curves for the two Sultanina vineyards in the warmer Summer Rainfall Region of the Northern Cape differed from the Winter Rainfall Region. Under warmer conditions this cultivar showed extended leaf activity and growth during the postharvest period.

Potential growth curves for the winter and summer rainfall regions could be estimated by means of third order polynomial equations using day of season as the independent variable and taking bud break as day one. It must be noted that application of these two curves will be limited to the Winter and Summer Rainfall Regions of South Africa, respectively. A further limitation is that variation between seasons were not addressed by this study. This should be investigated by further research. These models formed the foundation of a procedure by which actual leaf area could be estimated using fresh leaf mass measured on a specific day and time (day of season) as the input parameters. Results indicated that using cane mass to estimate maximum leaf area, which is needed for conversion of normalized leaf area to actual daily LAI values, would probably not be as accurate as using fresh leaf mass. This was most likely due to cultivar differences and variation in shoot water content at pruning. Furthermore, it was found that the relationship between maximum leaf area and cane mass varied between horizontal and vertical canopies. Horizontal canopies tended to produce more leaf area per unit cane mass in comparison to vertical canopies.

In agreement with earlier findings, water stored in the seasonal above-ground growth amounted to maximum values of about 7 millimetres. Over a seven month growing period, the net amount of water taken up daily over 24 hours and stored in the above-ground part of the grapevine would only amount to fractions of a millimetre. In calculating daily water consumption, water used for maintaining cell turgidity and physiological processes other than transpiration could be ignored.

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TABLE 5.1

Viticultural information of vineyards selected to determine leaf area development during the 1995/96-season.

Locality	Latitude	Climatic region *	Cultivar	Plant spacing	Trellising system
Stellenbosch	33°55'	III	Chenin blanc	3,0 m x 1,2 m	Lengthened Perold**
Stellenbosch	33°55'	III	Chenin blanc	3,0 m x 1,5 m	1,5 m Slanting trellis**
De Doorns	33°28'	V	Barlinka	3,0 m x 1,8 m	2,4 m Slanting trellis**
Robertson	33°50'	V	Emerald Riesling	2,75 m x 1,5 m	5-Strand vertical hedge***
Lutzville	31°36'	V	Colombar	2,75 m x 1,2 m	Factory trellis**
Lutzville	31°36'	V	Ruby Cabernet	2,75 m x 1,2 m	6-Strand vertical hedge***
Upington	28°27'	V	Sultanina	3,0 m x 1,5 m	2,4 m Slanting trellis**
Upington	28°27'	V	Sultanina	3,0 m x 2,0 m	Gable trellis**

* Winkler (1962)
** Zeeman (1981)
*** Booysen *et al.* (1992)

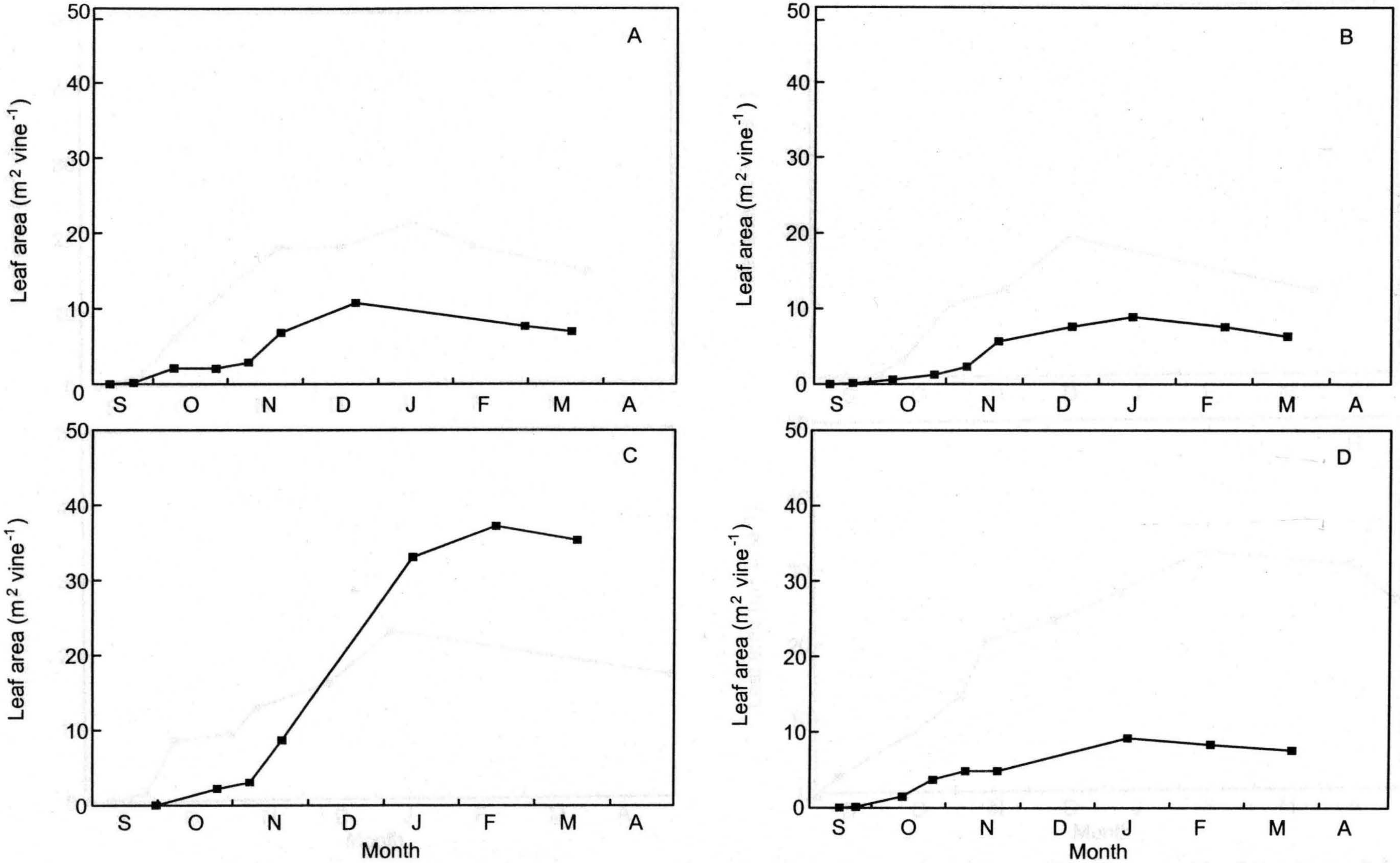

Figure 5.1. Variation in actual leaf area development of various vineyards measured during the 1995/96-season (A = Chenin blanc on 2,4 m slanting trellis at Stellenbosch, B = Chenin blanc on lengthened Perold at Stellenbosch, C = Barlinka on 2,4 m slanting trellis at De Doorns, D = Emerald Riesling on 5-strand vertical hedge at Robertson).

(Figure 5.1 Continued)

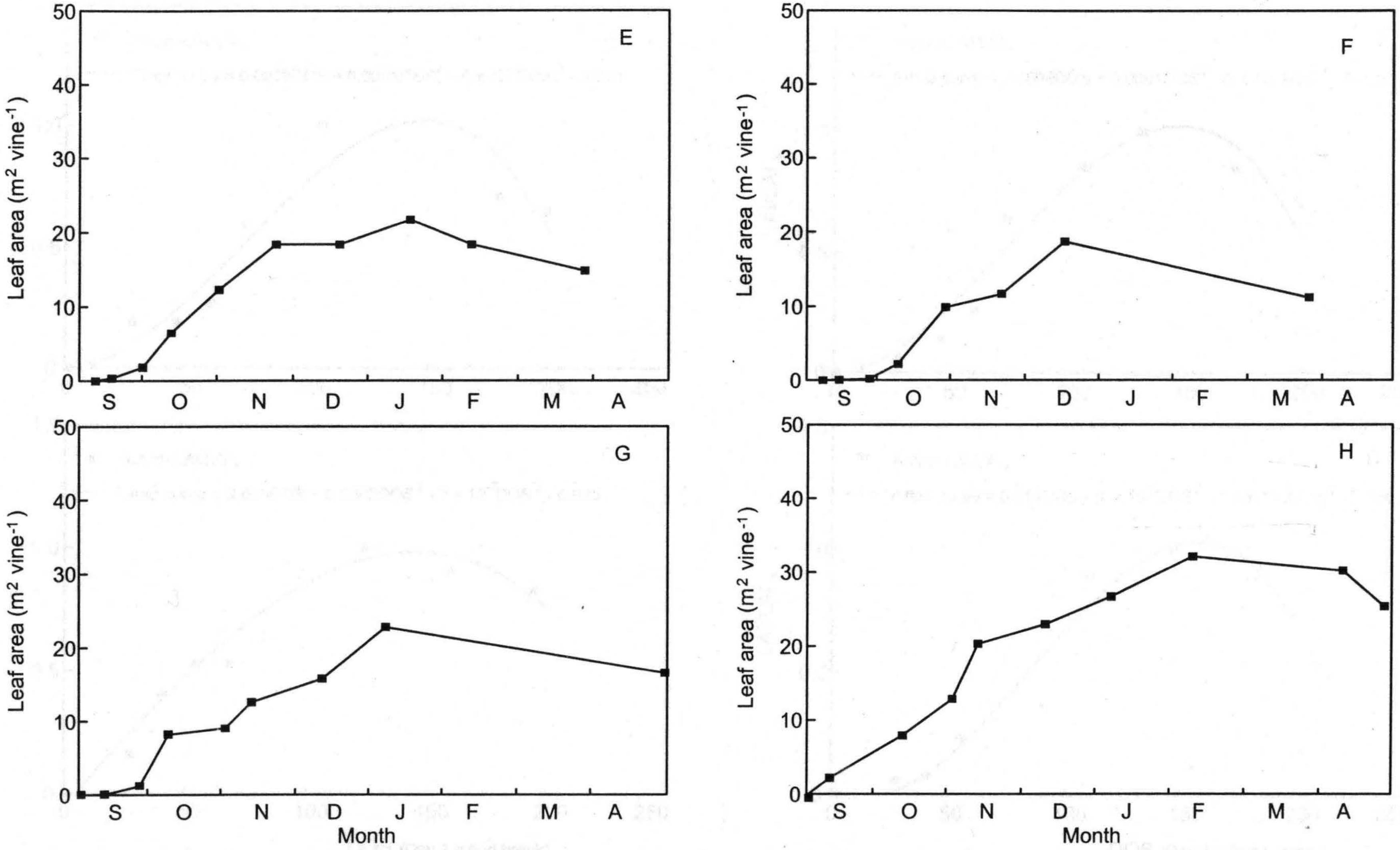

Figure 5.1 (Continued). Variation in actual leaf area development of various vineyards measured during the 1995/96-season (E = Colombar on 2,4 m slanting trellis at Lutzville, F = Ruby Cabernet on 6-strand vertical hedge at Lutzville, G = Sultanina on 2,4 m slanting trellis on alluvial soil at Upington and H = Sultanina on gable trellis on sandy soil at Upington).

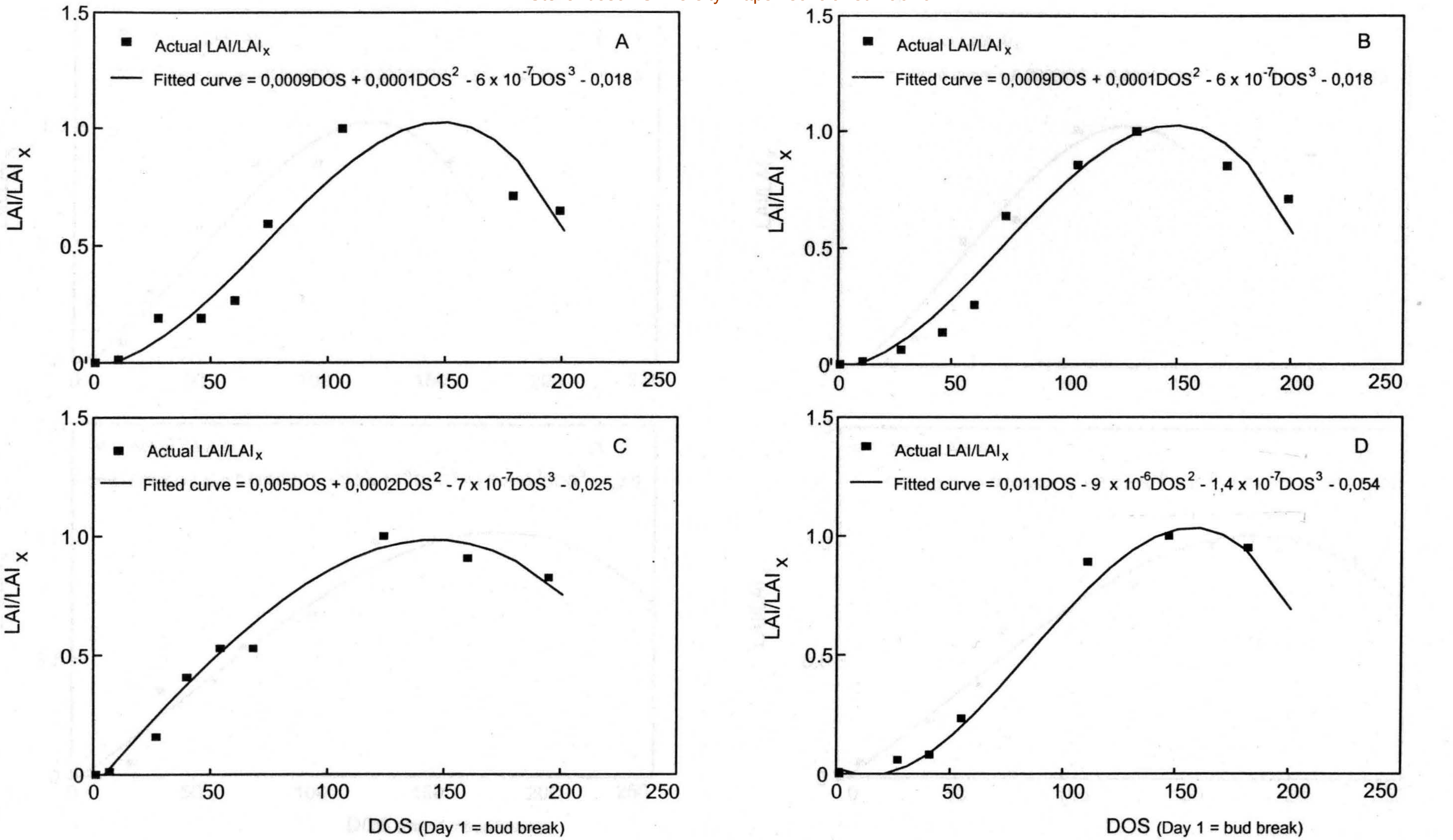

Figure 5.2. Potential growth curves based on normalized leaf area index (LAI/LAI$_x$) of various vineyards measured during the 1995/96-season (A = Chenin blanc on 2,4 m slanting trellis at Stellenbosch, B = Chenin blanc on lengthened Perold at Stellenbosch, C = Barlinka on 2,4 m slanting trellis at De Doorns, D = Emerald Riesling on 5-strand vertical hedge at Robertson).

(Figure 5.2 Continued)

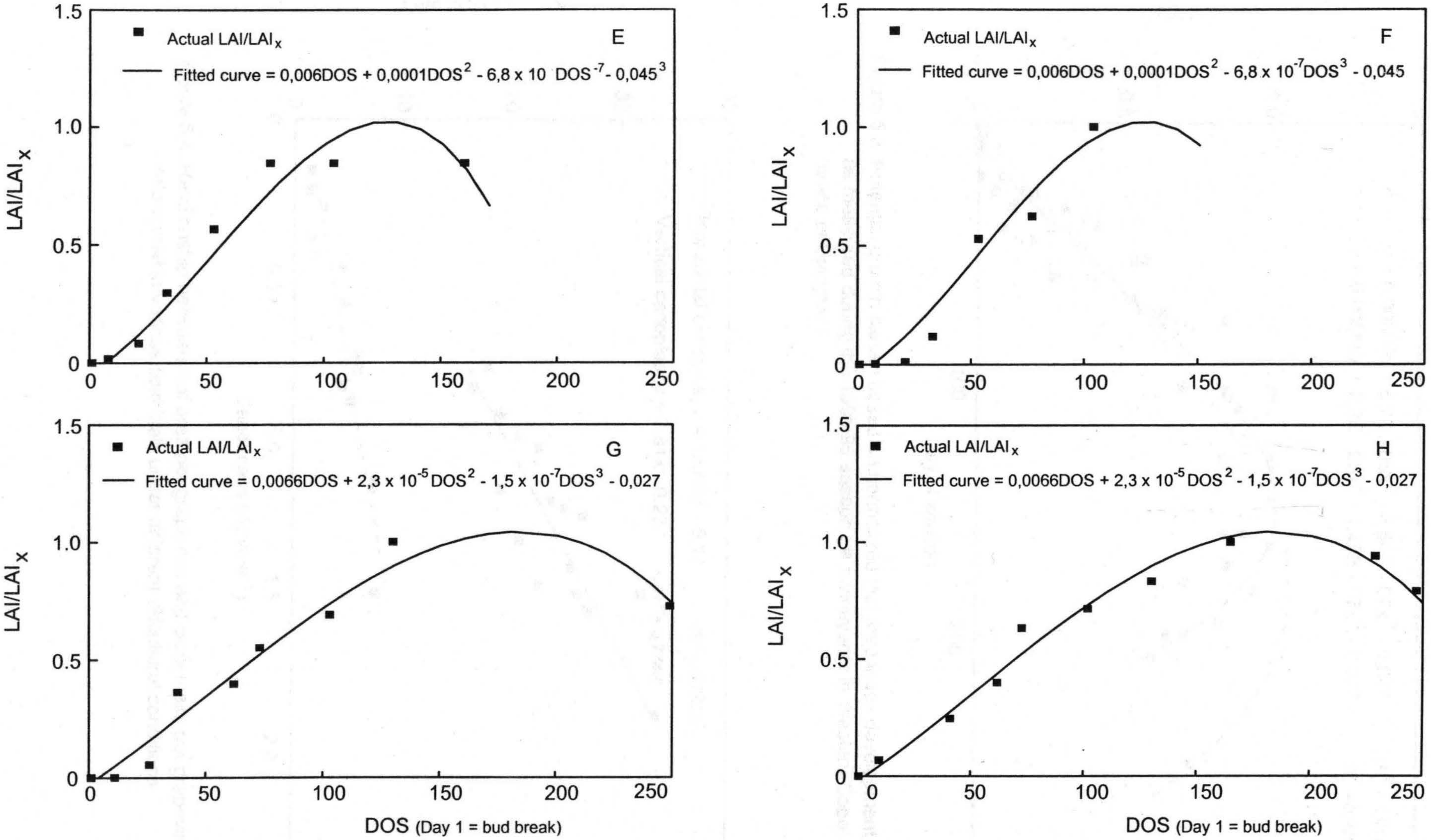

Figure 5.2 (Continued). Potential growth curves based on normalized leaf area index (LAI/LAI$_x$) of various vineyards measured during the 1995/96-season (E = Colombar on 2,4 m slanting trellis at Lutzville, F = Ruby Cabernet on 6- strand vertical hedge at Lutzville, G = Sultanina on 2,4 m slanting trellis on alluvial soil at Upington and H = Sultanina on gable trellis on sandy soil at Upington).

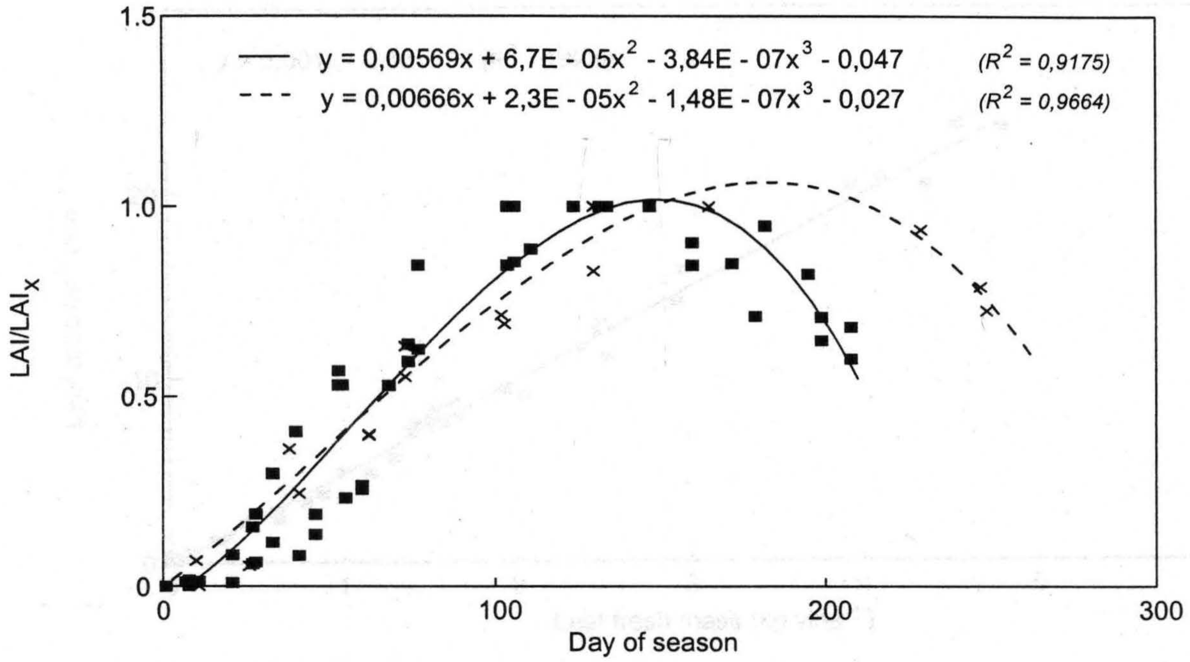

Figure 5.3. Potential growth curves based on normalized leaf area index development (LAI/LAI$_x$) as measured during the 1995/96-season (■ = vineyards in Western Cape; × = Sultanina at Upington).

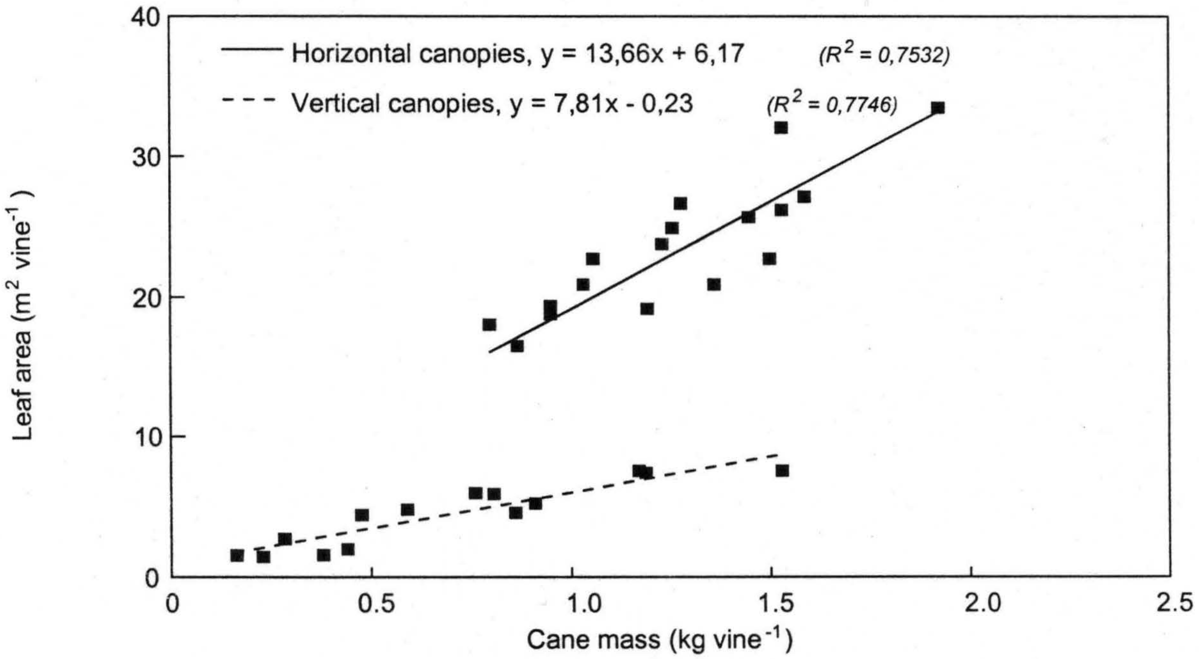

Figure 5.4. Relationship between leaf area per grapevine and cane mass per grapevine as determined in various field trials under different viticultural conditions.

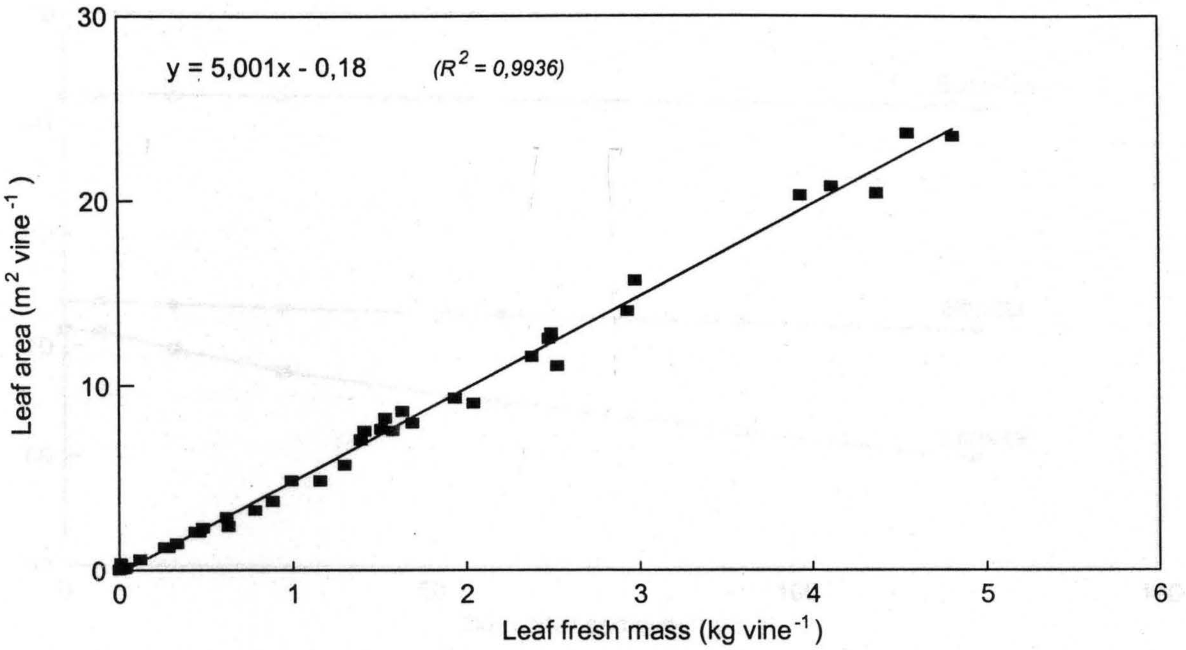

Figure 5.5. Relationship between leaf area per grapevine and total leaf fresh mass per grapevine as measured in eight vineyards during the 1995/96-season in various grape growing areas and under different viticultural conditions.

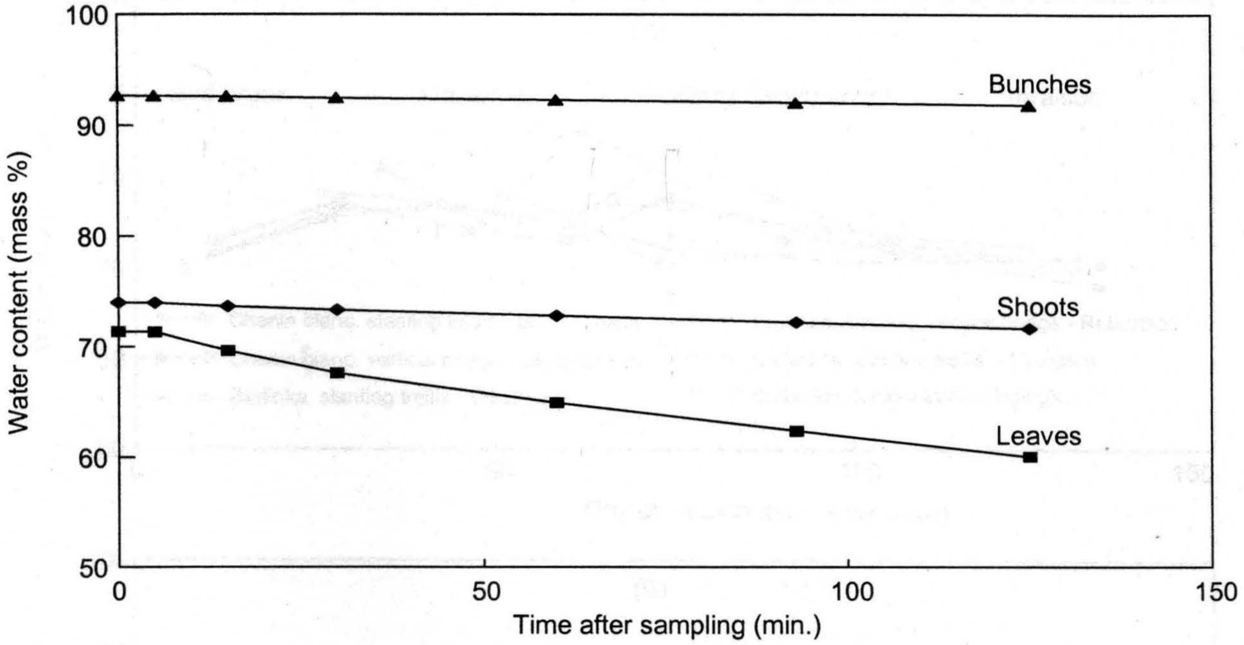

Figure 5.6. Variation in water content of leaves, shoots and bunches of Ruby Cabernet after sampling during December 1995 at Lutzville.

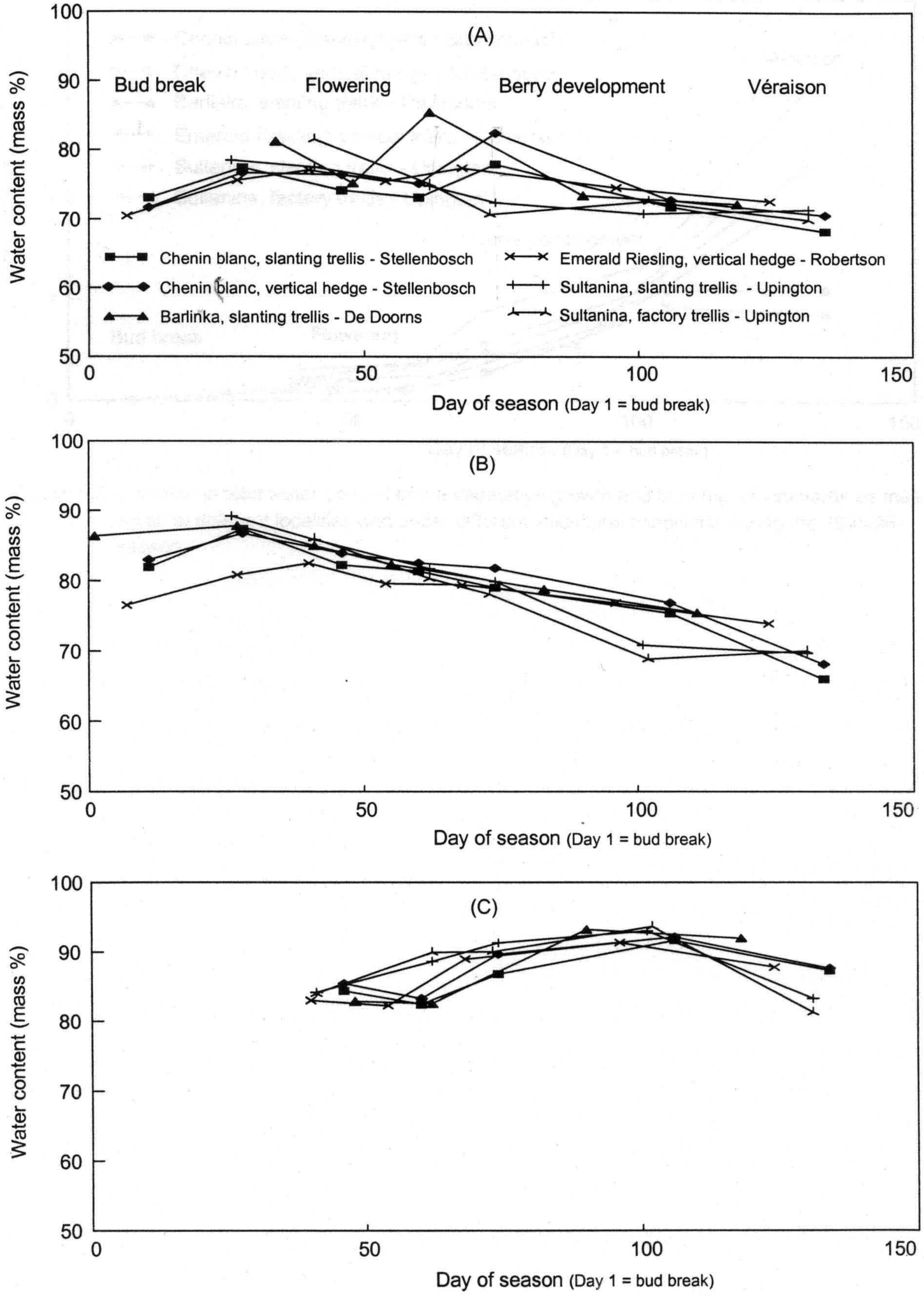

Figure 5.7. Seasonal variation in water content of (A) leaves, (B) shoots and (C) bunches of four grapevine cultivars as measured at different localities and under different viticultural conditions during the 1995/96-season.

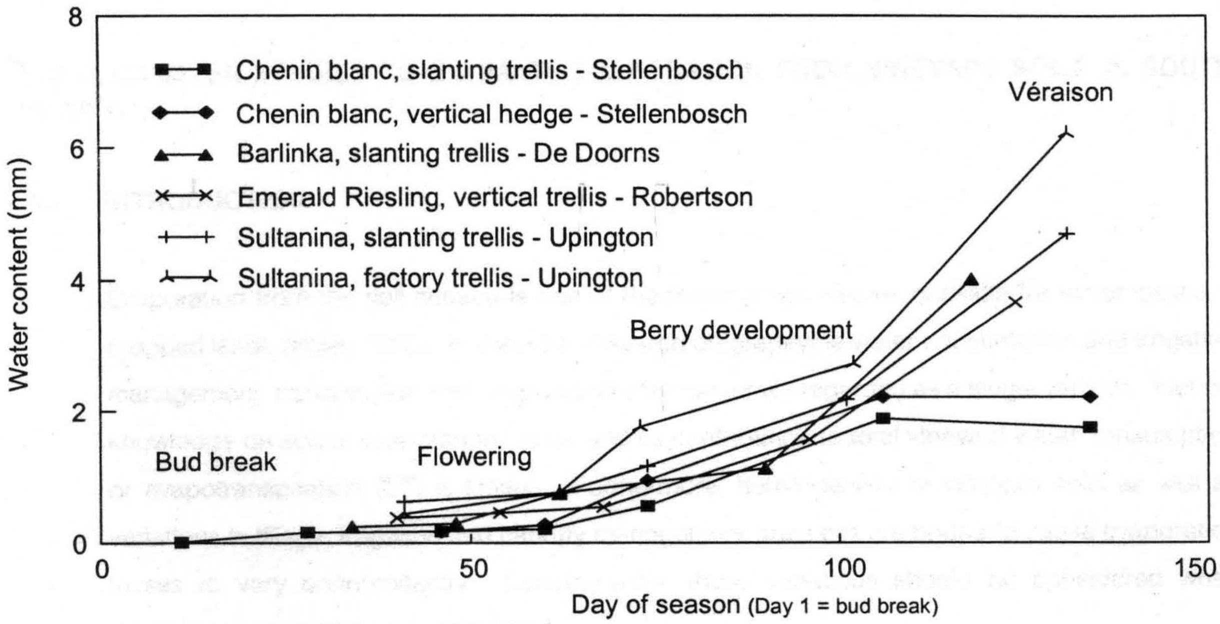

Figure 5.8. Variation in total water content of the vegetative growth and bunches of vineyards as measured at different localities and under different viticultural conditions during the 1995/96-season.

CHAPTER 6

MINI-LYSIMETER STUDIES TO ESTIMATE EVAPORATION FROM VINEYARD SOILS IN SOUTH AFRICA

6.1 INTRODUCTION

Evaporation from the soil surface is one of the major processes responsible for water losses in cropped lands (Hillel, 1980). In previous research on grapevine water consumption and irrigation management, transpiration and evaporation were generally regarded as a single variable. Hence, knowledge on actual evaporation losses and its contribution to total vineyard water consumption or evapotranspiration (ET) is limited. Furthermore, heterogeneity of vineyard soils as well as variations in tillage, irrigation and canopy management practices are bound to cause evaporation losses to vary concomitantly. Consequently, these variations should be considered when irrigation requirements are calculated.

According to Hillel (1980), evaporation from the soil surface after wetting by rain or irrigation takes place in three stages. Stage one, which is an initial, constant rate stage, occurs when the soil is wet and conductive enough to supply water to the site of evaporation at a rate equal to evaporative demand. During this stage, evaporation rate (E_s) is controlled by external meteorological conditions rather than by properties of the soil profile. However, soil surface conditions, such as reflectivity and the presence of a mulch, can modify effects of meteorological factors acting on the soil. In a dry climate, duration of stage one is generally short and may last only a few hours to a few days.

During stage two, which is an intermediate falling-rate stage, evaporation rate falls progressively below the rate of potential evaporation. At this stage E_s is determined by the rate at which the drying soil profile can supply water to the site of evaporation. Stage two may last for a much longer period than stage one. Eventually, a third residual slow-rate stage is established. Stage three may persist at a nearly steady rate for many days, weeks, or even months. During this stage, water transmission through the desiccated surface layer occurs primarily by the slow process of vapour diffusion. Hence, it is affected by the vapour diffusivity of the dried surface zone and the adsorptive forces acting over molecular distances at the particle surfaces (Hillel, 1980).

Measuring evaporation losses on a daily base can be time consuming and impractical. Consequently, various models have been developed to estimate evaporation from the soil surface. A combined water and energy balance model, as proposed by Van Bavel & Hillel (1976), could be used for simulation of evaporation from a bare soil surface. According to Lascano & Van Bavel

(1986), inputs to this model, which is referred to as CONSERVB, can be classified as time dependant variables, hydraulic functions, constants, and initial values. Time dependant inputs are solar radiation, air and dew-point temperature, wind speed and rainfall. Hydraulic functions are the soil water retention curve, the unsaturated hydraulic conductivity for each soil horizon, and the relationship between albedo and water content of the soil surface. Constants required are height of meteorological measurements, the surface roughness parameter, saturated hydraulic conductivity and soil porosity. Initial values are soil water content and soil temperature profiles, which must be measured or estimated at the start of a simulation period. When tested in a bare field with a smooth surface in Texas, CONSERVB predicted cumulative evaporation within one standard deviation of measured values (Lascano & Van Bavel, 1986). Daily evaporation rates could also be predicted within one standard deviation of the measured values, which ranged from 8 mm d^{-1} to 0,7 mm d^{-1}. The CONSERVB model was also evaluated by comparing predicted evaporation to measured values from a bare, tilled soil in New Zealand (Cresswell, Painter & Cameron, 1994). In this study, simulated evaporation was within 0,5 mm d^{-1} of the measured means on 18 of the 24 days simulated. It was found that evaporation prediction was sensitive to initial profile water content, the soil moisture characteristic curve and the unsaturated hydraulic conductivity inputs. Simulated daily evaporation could not be predicted to within 20 % of the measured values. Furthermore, it was reported that evaporation in the early stages of each drying cycle was overestimated and evaporation later in the cycles was underpredicted. It was suggested that this was due to inadequate simulation of redistribution of water within the soil profile.

In addition to problems arising from the accuracy of inputs for models such as CONSERVB, the detailed information, such as hydraulic conductivity and water characteristic are not always available for all soils. In this regard a simple model for predicting evaporation from bare soil was proposed by Malik, Anlauf & Richter (1992). This model, which is essentially based upon plate theory, delineates three classical and one transitional drying stage as the drying front advances into the soil profile. Daily soil surface evaporation is estimated from daily potential evaporation rate and depth of the drying front reached at the start of each day. Input parameters are daily potential evaporation rate, wilting point and field capacity moisture contents. Agreement between measured and predicted evaporation of twenty simulations were quantified by calculating mean relative deviation over the whole drying period. Mean relative deviations smaller than 4 % for all experiments, except one, were reported. Since model results could be influenced to some extent by choice of size of the depth and time steps, 40 mm and one day steps were used in all simulations. Depth of the first segment was always kept as 10 mm to increase sensitivity and accuracy. Distinct layers varying in texture or structure and cracks, which can influence upward water movement, were regarded as the major limitations to the applicability of this model.

Black, Gardner & Thurtell (1969) showed that by solution of the flow equation, and making a simple square root of time approximation, cumulative evaporation losses from an initially wet, deep soil could be estimated to within 5 % as follows:

$$E_s = C\,t^{0,5} \tag{6.1}$$

where E_s is evaporation from the soil surface (mm), C is cumulative evaporation constant and t is time (days) after field capacity was obtained by irrigation or rain. This approach was adopted in an evaporation model for row crops proposed by Ritchie (1972). The model describes a two-stage evaporation process. In the constant rate stage (stage one), the soil is sufficiently wet for water to be transported to the surface at a rate at least equal to the reference crop evapotranspiration (ET_o). The amount of drying required before soil water transport restricts evaporation is dependent on soil depth, hydraulic properties of the soil and the evaporative conditions. The end of stage one evaporation is reached when soil evaporation rate falls below ET_o. The cumulative evaporation amount for stage one drying (U) is mainly determined by the hydraulic properties of a specific soil. During stage one, cumulative soil evaporation $\sum E_s$ is calculated as follows.

$$\sum E_s = \sum ET_o \tag{6.2}$$

Equation 6.2 is valid until $\sum E_s$ = U, *i.e.* at the end of stage one. U is obtained when the soil evaporation rate begin to decline below the approximate daily ET_0 (Ritchie, 1972). When cumulative evaporation is in transition between stage one and stage two, $E_s = ET_o$ until $\sum E_s$ = U. For the rest of the day on which transition takes place E_s is arbitrarily taken as 0,6 ET_o.

In the falling rate stage (stage two), surface soil water content has decreased below a threshold value, so that E_s depends on the flux of water through the upper soil layer. Stage two evaporation is calculated using equation 6.1. The cumulative evaporation constant (C) is dependant on the hydraulic properties of the soil and can be determined experimentally from cumulative evaporation data for a single drying cycle. Comparing the model with evaporation determined by means of a weighing lysimeter, showed that the absolute error ranged between 0 mm day^{-1} and 0,9 mm day^{-1} when transpiration by a row crop was not considered. The cumulative evaporation constant is influenced by different reference crop evapotranspiration rates (Gill, Prihar & Arshad, 1992; Gill & Prihar, 1993) and cultivation (Gill & Prihar, 1993). Using this model under South African conditions where daily evaporation can vary significantly from day to day, will require continuous adaptations of C.

Due to this effect of ET on the cumulative evaporation constant during stage two, a parametric model containing only one easily measurable parameter was proposed by Boesten & Stroosnijder (1986). Their parametric model is mathematically described as follows :

$$\sum E_s = \sum ET_o \quad (\text{for } \sum ET_o < \beta^2, \textit{ i.e. } \text{stage 1}) \tag{6.3}$$

$$\sum E_s = \beta(\sum ET_o)^{0,5} \quad (\text{for } \sum ET_o > \beta^2, \textit{ i.e. } \text{stage 2}) \tag{6.4}$$

$$E_s = \sum E_{s,n} - \sum E_{s,n-1} \tag{6.5}$$

In the above equations E_s is the actual soil evaporation in mm d^{-1}, ET_0 is reference crop evapotranspiration in mm d^{-1}. The summation indicates cumulative evaporation in mm and n is the day number. β ($mm^{0,5}$) is an evaporation characteristic soil parameter to be determined experimentally from the slope of the $\sum E_s$ *versus* $(\sum ET_o)^{0,5}$ curve. The amount of water that can evaporate during stage one, is equal to β^2 (mm). Analysis of evaporation data revealed that, for constant ET_o conditions of 4 mm d^{-1}, 8 mm d^{-1} and 16 mm d^{-1}, β-values only differed by 10 %. Hence, β was considered as a constant or independent of ET_o by Boesten & Stroosnijder (1986).

Most of the models mentioned above were developed and evaluated for prediction of evaporation from bare soil. It was suggested by Ritchie (1972) that repartitioning of a large fraction of net radiation at the dry soil surface between plant rows to sensible heat flux, increased canopy temperature and consequently increased evaporation from the plant canopy. When soil and canopy energy balances were determined in a west Texas vineyard, it was found that generated sensible heat at the soil surface was transferred to the canopy (Heilman, McInnes, Savage, Gesch & Lascano, 1994). This effect produced canopy latent heat flux densities which were in excess of canopy net irradiance. On the contrary, it was found that heat produced in a maize canopy and transported to wet soil surfaces could cause soil evaporation to be higher than potential evaporation (Walker, 1984). Thus, it is clear that evaporation from the soil should be studied under field conditions in order to consider soil-canopy heat exchange effects. Furthermore, when plants are present, water can be extracted by transpiration to such an extent that water content and water flow to the surface are reduced (Hanks, 1991). In this regard a root extraction term was added to the one-dimensional water flow equation which is used to predict soil water losses in a evapotranspiration model proposed by Hanks (1991).

Mulching is applied in vineyards either directly by adding a cover material or indirectly by cultivating a cover crop which eventually acts as a mulch after it is killed by means of herbicides and flattened before bud break. Mulching can reduce evaporation losses from the soil surface (Hillel, 1980). However, usually only the initial evaporation rate, *i.e.* during stage one, is reduced.

This means that water is saved if rains are frequent, or irrigation cycles are short. Conserving water by limiting evaporation through mulching was also observed by Van Huyssteen, Van Zyl & Koen (1984). In this study, it was found that a Wimmera rye grass mulch was superior to a Vetch mulch in reducing evaporation. Jalota (1993) showed that vapour flux densities through a dry soil mulch decreased when mulch thickness was increased from 5 mm to 75 mm. By comparing wheat straw mulches of 4 t ha^{-1}, 8 t ha^{-1} and 12 t ha^{-1} in a field trial, Van Zyl & Myburgh (1997) found that cumulative evaporation decreased substantially with an increase in mulch thickness. However, due to decay and weathering this effect became less significant during the later stages of the season. Van Huyssteen & Weber (1980) found that, due to larger grapevines and canopies, which resulted in higher transpiration losses, the positive water conservation effect of a 7 t ha^{-1} straw mulch under dryland conditions also decreased as the season progressed. From the foregoing it is evident that mulching effects should be considered when developing a model for estimation of evaporation in vineyards. In developing the above-mentioned models only evaporation from an unmulched soil surface was accounted for. Consequently, these models would not be applicable to mulched soil surfaces which are commonly encountered in South African viticulture.

Various methods have been applied to measure actual E_s (evaporation from the soil surface) in either field or laboratory studies. Of these methods, the micro-lysimeter technique as proposed by Boast & Robertson (1982) was used in a number of field studies (Boesten & Stroosnijder, 1984; Lascano & Van Bavel, 1986; Lascano & Hatfield, 1992; Heilman *et al.*, 1994; Mwendera & Feyen, 1997). These micro-lysimeters are approximately 100 mm long with an inner diameter of 76 mm. A weighing lysimeter, 2,27 m^2 in cross section and 1,10 m deep, which recorded lysimeter mass every 15 minutes, was used in a study to validate the Ritchie and Boesten & Stroosnijder models in Western Australia (Yunusa, Sedgley & Tennant, 1994). The neutron scattering technique was used to measure evaporation losses from undisturbed soil monoliths of 236 mm diameter and 600 mm long (Johns, 1982). Neutron loss through the sides and ends of monoliths, however, required careful calibration procedures. Evaporation studies were also performed in laboratories on soil columns packed in PVC tubes (Gill & Prihar, 1983; Gill, Prihar & Arshad, 1992). These columns were 950 mm long with an inner diameter of 100 mm. Stroosnijder (1987) used gravimetric soil sampling to effectively determine water loss in a study performed in Mali. This method was also used by Van Zyl & Myburgh (1997). Time domain reflectometry (TDR) was used to measure evaporation from field plots (Plauborg, 1997).

Since most of the evaporation models discussed in the foregoing did not address canopy/evaporation interactions or variation in surface conditions, they are not directly applicable to vineyards. A further disadvantage of some models is the large number of inputs required to obtain accurate estimations. Determining inputs such as hydraulic conductivity, would also be impractical if a model has to be applied on a commercial scale. Hence, the simple Boesten & Stroosnijder model, which required limited inputs and was shown to have acceptable accuracy, could be regarded to be suitable as a first approach in modelling evaporation from vineyard soils.

The aims of this study were: (i) to measure evaporation losses under grapevine canopies, and (ii) to evaluate and adapt the Boesten & Stroosnijder model for estimation of evaporation from vineyard soils.

6.2 MATERIALS AND METHODS

6.2.1 Soil samples

Soils used in the lysimeter study were selected to be representative of typical topsoils found in grape growing regions of South Africa. Soils were also selected to obtain a range of clay contents. A coarse sandy soil was sampled at the ARC-Infruitec/Nietvoorbij Experimental Station near De Doorns in the Hex River Valley which is regarded as one of the major table grape growing regions of South Africa. A sandy loam soil was sampled at the ARC-Infruitec/Nietvoorbij Experimental Station near Robertson in the Breede River region where primarily wine grapes are produced. A sandy clay loam soil with a high gravel content was sampled in a vineyard at the ARC-Nietvoorbij Centre for Vine and Wine in the Stellenbosch wine region. An alluvial sandy loam soil was sampled at the Department of Agriculture Northern Cape Experimental Station situated near Upington in the Lower Orange River Valley where most of South Africa's raisin grapes and a large quantity of table as well as wine grapes are produced. A red, sandy soil was also sampled near Upington at the SADOR farm of the South African Dried Fruit Co-operative. An appreciable amount of the table grapes in the Lower Orange River are produced on this soil type. The sixth soil was sampled in a vineyard at the ARC-Nietvoorbij Centre for Vine and Wine. This soil was selected to represent a structureless, loamy topsoil commonly found in the Western Cape. The soil forms to which the six above-mentioned soils belong according to Soil Classification Work Group (1991) are presented in Table 6.1. Since most evaporation losses occur from the topsoil, only these layers were used in this study. The samples were therefore not necessarily representative of the specific soil form. Other soil forms might have similar topsoils or A-horizons.

At each site *ca* 400 kg bulk samples of the 0 mm to 150 mm and 150 mm to 300 mm depths were sampled separately. Subsamples of the two depth increments of each soil were taken for particle size analyses of the <2,0 mm fraction. Particle size diameter classes were, <0,002 mm (clay) 0,002 mm - 0,02 mm (silt), 0,02 mm - 0,2 mm (fine sand), 0,2 mm - 0,5 mm (medium sand) and 0,5 to 2,0 mm (coarse sand). Soil textural classes were obtained using standard diagrams (Soil

Classification Work Group, 1991).

6.2.2 Lysimeter construction and filling

Lysimeters consisted of 360 mm x 360 mm x 300 mm deep rectangular asbestos containers with four 10 mm diameter holes drilled in the bottom to allow drainage. Four 3 mm x 20 mm x 300 mm flat-iron strips were bolted to the sides of the containers (Fig. 6.1). These strips protruded 15 mm above the upper edge. Holes were drilled in the protruding sections to enable attachment of hooks for lifting and transportation. Lysimeters were painted on the inside and outside using an universal undercoat and two layers of white enamel paint to avoid water absorption by the container. After numbering the lysimeters, the mass of each one was recorded. Inside dimensions and depths were measured to calculate the exact volume of each lysimeter. In relation to the relatively small lysimeters used by Boast & Robertson (1982) and the size of the one used by Yunusa *et al*. (1994), lysimeters used in this study will be referred to as mini-lysimeters in further discussions.

On the day prior to filling the mini-lysimeters, bulk soil samples were moistened and mixed thoroughly. After taking samples in triplicate for gravimetric assessment of soil water content, bulk soil samples were tightly covered by means of canvas sheets to limit evaporation losses during the night. Gravimetric soil water content was determined after drying at 105 °C for 16 hours.

The mini-lysimeters were filled by adding loose soil in increments with known mass. After each addition the soil was compacted lightly using a wooden pole. The original layer sequence was maintained in the filling process. After filling the first mini-lysimeter, the bulk density of each layer was calculated as follows:

$$\varrho_b = \frac{M}{(\theta_g + 1) \times V} \tag{6.6}$$

where, ϱ_b is bulk density (Mg m^{-3}), M is mass of moist soil (kg), θ_g is gravimetric soil water content, and V is volume of the specific mini-lysimeter (m^3). Rewriting equation 6.6 to calculate moist soil mass, a further nine mini-lysimeters were filled to the same bulk density as the first. A similar procedure was followed to fill ten mini-lysimeters with each soil type. This resulted in a unique bulk density for each soil type. Five mini-lysimeters containing each soil type were covered by means of 0,10 kg wheat straw to simulate a mulch equivalent to 7,7 ton ha^{-1}, while the other five were left unmulched. Wire grids with 10 mm x 30 mm openings were placed over the mulch to prevent it from blowing away and to avoid disturbance by birds.

6.2.3 Experimental layout

During September 1993, mini-lysimeters containing the De Doorns coarse sand and the Robertson sandy loam soil, were installed in a 12 year old Chenin blanc vineyard on the ARC-Nietvoorbij Centre for Vine and Wine at Stellenbosch. Vines were planted 3,0 m x 1,5 m and trained onto a 1,5 m slanting trellis (Zeeman, 1981). Vine rows were orientated in a North-South direction. The 1,0 ha experimental vineyard was surrounded on all four sides by vineyards with similar row orientation.

The five mini-lysimeters which contained a specific soil type/surface treatment combination were installed diagonally across the work row (Fig. 6.2). Diagonal mini-lysimeter rows were 10 m apart. Square pits were excavated to accommodate the mini-lysimeters in such a way that the lysimeter soil surface was at the same level as the surrounding soil surface. To retain loose soil, pits were lined with wooden frames. The bottom of each pit was covered by a 150 mm coarse sand layer to absorb possible drainage water (Fig. 6.1). The five mini-lysimeters containing a specific soil type/surface treatment combination were regarded as a single replication which measured average evaporation between two vine rows.

During August 1994, the lysimeter study was expanded as follows. Mini-lysimeters containing the De Doorns coarse sand and Robertson sand loam soils were installed in a 12 year old Sauvignon blanc vineyard adjacent to the previous one. However, in this vineyard vines were trained onto a 5-strand lengthened Perold trellis (Booysen et al., 1992). Vines were also planted 3,0 m x 1,5 m. Mini-lysimeters containing the Upington sand loam and Stellenbosch sand clay loam soils were installed in the slanting trellis vineyard. Saturation and soil water loss measurements of the four soils were obtained during the 1994/95-season from budbreak until leaf fall. During the 1995/96-season, mini-lysimeters containing the alluvial sand loam and the high gravel content sand clay loam were installed in the vertically trellised vineyard. Further treatment application with regard to the Upington sand and the Stellenbosch loam soil are presented in Table 6.1.

6.2.4 Lysimeter operation

Soils were saturated by applying water with a removable drip line designed so that a 4 ℓ h^{-1} dripper supplied water at the centre of each lysimeter. After saturation, mini-lysimeters were covered by means of galvanized metal lids to limit evaporation losses and left overnight to allow drainage and redistribution. The following morning lids were removed and each mini-lysimeter lifted onto a balance. The balance had maximum capacity of 100 kg and allowed mass recording to the nearest 0,02 kg. After recording the mass, mini-lysimeters were replaced without lids. Mini-lysimeters were weighed daily at 08:00, except during weekends. Evaporation runs generally lasted fourteen days. During the first two seasons (1993/94 and 1994/95) an average of two runs per month were maintained. However, due to limited labour and time, runs were scaled down to one run per month during the 1995/96- and 1996/97-seasons. Weed control was obtained by applying systemic herbicide (glyphosate) as weeds emerged. Lysimeters studies commenced at budbreak (September) and were terminated at the onset of leaf fall (May).

At saturation, total mass of a mini-lysimeter amounted to approximately 77 kg depending on the bulk density and water content of the specific soil type. For this reason two persons were needed to lift a mini-lysimeter onto the balance, while a third recorded the mass. It generally took 50 minutes to weigh forty lysimeters. The process was slower under windy conditions when accurate measurements could only be accomplished between gusts.

Based on the lysimeter soil surface area, soil water losses of 0,15 mm, which were equivalent to 0,02 kg of water, could be recorded by means of the mini-lysimeters. Generally evaporation never reached such low levels during the 14 day runs. This suggested that mini-lysimeters allowed accurate evaporation measurement under field conditions during this study.

6.2.5 Soil bulk density

After two seasons, mini-lysimeters were removed from the vineyard. Bulk density of the 0-150 mm and 150-300 mm depth layers were determined in five mini-lysimeters of each soil type by means of the undisturbed core method. Soil core diameters were 73 mm and volumes were 2,77 x $10^{-4}$$m^3$.

6.2.6 Saturated hydraulic conductivity

This parameter was determined on undisturbed soil cores using the constant head method described by Klute & Dirksen (1986). Soil cores were sampled in five mini-lysimeters per soil type at the same time as the bulk density samples. Soil core diameters were 54 mm and volumes were 7,10 x 10^{-5} m^3. Due to practical considerations, saturated hydraulic conductivity was measured on only three samples of the 0 - 150 mm depth layer of each of the six soils.

6.2.7 Meteorological parameters

Daily pan evaporation (E_p) was measured using an American Class A-pan situated 1 km from the experimental vineyard. Radiation, windspeed as well as wet and dry bulb air temperature were recorded hourly by means of an automatic recording weather station (MC- Systems). This station, which was installed next to the slanting trellis vineyard, only came into operation during July 1995. Daily reference crop evapotranspiration (ET_o) was calculated using a modified Penman-Monteith equation (De Jager, Van Zyl, Kelbe & Singels, 1987) as presented in Chapter 3.

Daily evaporation measured by means of the American Class-A pan (E_p) showed poor correlation with reference crop evapotranspiration (ET_o) calculated by means of automatic weather station data and the modified Penman-Monteith equation (Fig. 6.3A). The discrepancy between E_p and ET_o was more pronounced for the higher range of E_p values. However, when daily E_p was corrected for variations in wind speed and relative humidity using Table 6.2 (Doorenbos & Pruitt, 1977), the slope of the regression was almost one (Fig. 6.3B). Consequently, all E_p data were corrected using Table 6.2 for periods during which ET_o data were not available.

6.2.8 Statistical analyses

Due to practical limitations, treatments could not be replicated. However, statistical analyses of the data, which also included assessment of variation in evaporation across the work row over time, were obtained by using the half normal points diagram technique as described by Calitz (1989). Evaporation data obtained one day, three days and ten days after an irrigation was applied, were used in the statistical analyses. These evaporation data were mean values of measurements made during runs at the beginning, middle and end of the growing season. SAS was used for the analysis of variance. STATGRAPHICS was used for linear regression analysis.

6.3 RESULTS AND DISCUSSION

6.3.1 Soil physical parameters

Texture : Particle size analyses and soil textural classes are presented in Table 6.3. Clay contents for the selection of soils ranged between 2,01 % and 25,15 %. These values are typical for South African vineyard topsoils. The silt content for the Stellenbosch loam was surprisingly higher compared to the alluvial Upington fine sand loam which was expected to have a high silt content due to its pedogenesis. Most soils contained fairly high fine sand fractions. With the exception of the Stellenbosch sand clay loam, all soils were gravel and stone free in their natural state.

Soil bulk density : Bulk densities are presented in Table 6.3. Although packed soil bulk densities appeared to be relatively high, this is not unrealistic since natural and mechanical compaction to these densities and higher are not uncommon in South African vineyard soils (Van Huyssteen, 1989). The relatively high bulk density of the Stellenbosch sand clay loam was caused by the high particle size density of the large quartz gravel fraction.

6.3.2 Evaporation patterns across the work row

Variation in evaporation (E_s) from unmulched soil did not show consistent patterns across the work row. However, for some soils E_s tended to be higher in the middle section of the row one day after irrigation, *i.e.* at positions two, three or four (Fig. 6.4, 6.5, 6.6, 6.7, 6.8, 6.9). The tendency towards lower E_s values measured at positions one and five, *i.e.* nearest to the grapevine rows, were probably due to shading by the foliage and trellis system. In some cases shading significantly reduced evaporation at these positions (Fig. 6.4A, 6.5A & B, 6.6A & B, 6.7A, 6.9B). In most cases the lowest E_s was measured on the western side of the work row, *i.e.* at position five. The shading effect diminished as the soil dried out and at three and ten days after irrigation, evaporation was practically constant across the work row. This suggested that measuring evaporation across the work row to obtain reliable and representative results, is only vital during the first day or two after irrigations.

In the case of mulching, shading had no significant effect at any stage after irrigation. Consequently, evaporation from mulched soil could be considered as constant across the work row, irrespective of time after irrigation (Fig. 6.4, 6.5, 6.6, 6.7, 6.8, 6.9). Mulching also negated shading effects by the vertical canopy on evaporation across the work row during all stages of the drying cycle. These results confirmed that representative evaporation may be measured at a single position in the work row if the soil is mulched.

In this study canopy orientation had no significant effect on evaporation patterns across the North-South work rows.

6.3.3 Estimating evaporation from unmulched soil

Evaporation during stage one : Variations in monthly average slopes (m_1) of the relationship between cumulative soil evaporation ($\sum E_s$) and cumulative reference crop evapotranspiration ($\sum ET_o$) during stage one evaporation are presented in Table 6.4. Individual m_1 values obtained for each evaporation run were averaged on a monthly basis. In the case of the gravelly Stellenbosch clay loam soil, stage one evaporation generally lasted for less than a day. Since E_s was only measured daily, realistic m_1 values could not be obtained for this specific soil. Apparently soil texture had no effect on the slope (m_1) of the $\sum E_s$ versus $\sum ET_o$ relationship. This was to be expected since E_s is primarily a function of climatic conditions during stage one evaporation (Hillel, 1980). Trellising system also had no particular effect on m_1. However, m_1 generally tended to decrease until the middle of the growing season as vegetative growth increased (Fig. 6.10). This was probably due to increased shading by the grapevine canopy and trellising system. Seasonal variation in sun angle and incidence of net radiation beneath the grapevine canopies could also have contributed towards seasonal variation in m_1.

In most previous laboratory and field studies of soil evaporation, $\sum E_s$ was equal to $\sum ET_o$ during the first stage of evaporation. In these studies, evaporation losses were determined for bare, fallow soil (Boesten & Stroosnijder, 1986) or bare, tilled soil (Stroosnijder, 1987; Yunusa *et al*, 1994; Rose, 1996; Plauborg, 1997). Hence, canopy effects could not be accounted for. Furthermore, in presenting a model for predicting evaporation from a row crop with incomplete cover, the effect of vegetation on m_1 during stage one evaporation was not considered (Ritchie, 1972).

Evaporation during stage two : Examples of cumulative E_s *versus* square root of cumulative ET_o plots are presented in Figures 6.11, 6.12, 6.13. In contrast to stage one evaporation, soil type had an effect on evaporation during the second stage when hydraulic properties also determine the rate of water loss. Average slopes or β-values ranged between 2,15 $mm^{0,5}$ for the Stellenbosch sand clay loam and 4,68 $mm^{0,5}$ for the De Doorns sand (Table 6.5). In general, slopes of cumulative evaporation ($\sum E_s$) *vs.* square root of cumulative reference evaporation $(\sum ET_o)^{0,5}$ were higher in comparison to some values established by previous research. Beta-values of 1,5 $mm^{0,5}$ for a loamy sand (Boesten & Stroosnijder, 1986) and 1,65 $mm^{0,5}$ for a clay loam soil (Stroosnijder, 1987) were established by means of micro-lysimeters and gravimetric soil samples, respectively. Estimating $\sum E_s$ for a fine textured Xeralfic Alfisol, using β-values which varied between 1,35 $mm^{0,5}$ and 1,50 $mm^{0,5}$, produced good agreement with actual $\sum E_s$ measured by means of a weighing lysimeter (Yunusa *et al*, 1994). On the other hand, Plauborg (1997) showed that a β-value of 6,5 $mm^{0,5}$ had to be used for prediction of $\sum E_s$ as determined under undisturbed field conditions.

Results adapted from previous evaporation studies suggest a linear relationship between column height and duration of phase one (Fig. 6.14). Furthermore, in verifying the micro-lysimeter technique, Boast & Robertson (1982) has shown that column length did affect the total amount of water lost over time for column heights ranging from 20 mm to 146 mm. Since 300 mm high soil columns were used in this study, it could explain the higher evaporation rates in comparison to values obtained by means of 100 mm high columns. Loose soil at the surface of tilled soil used in previous studies could also have reduced evaporation rates or β-values (Gill & Prihar, 1983). However, in most vineyards minimum tillage is applied and consequently soil surfaces are slightly consolidated throughout the growing season. Hence, it would be more realistic to obtain β-values by using soils with slightly consolidated surface conditions as was the case for soils in the mini-lysimeters in this study. Considering the uncertainty regarding the use of lysimeters in general, methods to measure evaporation from undisturbed field soils should be pursued by future research.

6.3.4 Relating β-values to canopy and soil properties

Canopy orientation : Beta-values tended to be higher for the horizontal canopy in comparison to the vertical canopy (Table 6.5). The only exception was the Stellenbosch sand clay loam soil. This suggested that canopy effects were negated when evaporation rates were inherently low. The larger distance between soil surface and foliage possibly allowed more air flow under the slanting trellis compared to the vertical hedge where the foliage was much closer to the soil surface. This would mean that vertical canopies had a more pronounced wind break effect on evaporation from the soil surface. In this study row direction was north-south so that it was quite possible that the vertical canopy acted as a barrier to the prevailing south easterly and north westerly winds. However, if the row direction was more parallel to the prevailing wind directions, differences in β-values due to the wind break effect, would probably have been less prominent. These findings are in agreement with previous research which showed that average air movement measured in the middle of the work row at bunch height amounted to 27,63 km d^{-1} and 15,87 km d^{-1} under a slanting trellis and a vertical lengthened Perold system, respectively (Van Zyl & Van Huyssteen, 1980). Higher resistance to air flow by the vertical hedges was regarded as the reason for this effect. Although the degree of shading may be higher under a horizontal trellis, it can be assumed that wind has a more prominent effect on evaporation compared to shading.

According to Walker (1984), it is also possible that air heated in the upper canopy during the daytime could be swept down by large eddies to serve as an additional source of energy for evaporation. This conclusion was based on higher net sensible heat flux measured in maize canopies of LAI 4,0 in comparison to less dense canopies with LAI 3,0. Similar effects could also have contributed to the tendency toward higher evaporation losses under the larger horizontal trellis system.

Under the conditions of this study, β-values for a specific soil type did not decrease as foliage cover increased, but tended to remain constant over the growing season. No prominent seasonal tendencies were observed in comparison to stage one evaporation. This suggested that an increase in foliage had no effect when evaporation rates were relatively low during stage two.

Soil bulk density : Variation in β-values could not be related to variation in bulk density of the 0-150 mm or the 150-300 mm soil layers (Fig. 6.15). In the case of the De Doorns sand, the relatively high bulk density of the compacted soil in comparison to field values of 1,49 Mg m^{-3} (Myburgh, 1996) could have been responsible for the high β-values due to improved hydraulic conductivity. However, β-values of 6,5 $mm^{0,5}$ were related to a loamy sand soil with bulk densities between 1,0 Mg m^{-3} and 1,3 Mg m^{-3} (Plauborg, 1997). It can be assumed that the difference between field and lysimeter bulk densities had no significant effect on β-values obtained by means of the mini-lysimeters.

Soil texture : Beta-values tended to decrease almost linearly with an increase in clay content (Fig. 6.16A). A similar relationship was found between β-values and silt content (Fig. 6.16B). However, β-values for the Stellenbosch loam soil deviated significantly from the linear relationship for clay as well as silt content. Since particle size analysis data for this specific soil correspond to data reported by Van Huyssteen (1977) for the same experimental site, errors in the analysis process could not be the cause for the discrepancy. Hence, at this stage there is no explanation for the behaviour of this specific soil. These results suggested that neither clay content nor silt content, could be regarded as reliable indicators of variation in β-values.

No correlation was found between β-values and each of the three sand fractions (Fig. 6.16C, D & E). However, β-values tended to increase linearly with an increase in total sand content except in the case of the Stellenbosch loam soil (Fig. 6.16F). As for clay and silt, total sand content could not be used to account for the variation in β-values.

Saturated hydraulic conductivity : Beta-values, which were determined under unsaturated conditions, tended to increase linearly with an increase in saturated hydraulic conductivity (Fig. 6.17). Since β^2 is the upper limit of what can evaporate during stage one, *i.e.* when soils are at, or near saturation, it might explain the positive correlation between β and saturated hydraulic conductivity (K_s). The Stellenbosch sand clay loam soil proved to be a significant outlier. This deviation was probably the result of preferential flow due to the gravelly nature of the soil (Table 6.3) which caused non-Darcian flow behaviour. Hence, K_s is not reliable to explain the variation in β-values.

Since soil water flow during stage two evaporation occurs under unsaturated conditions, measuring unsaturated hydraulic conductivity would probably be more suitable to explain variations in β-values. Determining unsaturated hydraulic conductivity was beyond the scope of this study and needs to be addressed by further research.

6.3.5 Estimating evaporation from mulched soil

Similar to clean tilled surface conditions, evaporation from mulched soils decreased with time (Fig. 6.4, 6.5, 6.6, 6.7, 6.8 & 6.9). This decrease, however, was not as significant in comparison to bare soil. When related to cumulative reference crop evapotranspiration ($\sum ET_o$), cumulative soil evaporation of mulched soils ($\sum E_s$) increased linearly (Fig. 6.18, 6.19 & 6.20). Hence, there were no distinctive stages compared to evaporation from bare soils under the same climatic conditions and time span. This linearity was also maintained for the longer runs in the case of the Upington sand and the Stellenbosch loam (Fig. 6.19). Average slopes of $\sum E_s$ *versus* $\sum ET_o$ curves varied between 0,18 for the Stellenbosch sand clay loam and 0,44 for the Stellenbosch loam, both under vertical trellising systems (Table 6.6). In general, $\sum E_s$ was approximately 30 % of $\sum ET_o$ for most soil types when mulched.

As for unmulched soil, $\sum E_s$ tended to be higher under the horizontal trellis system than the vertical trellis system. Possible reasons for this tendency were discussed in section 6.3.3. Higher $\sum E_s$ values measured under the vertical trellis in the case of the Upington sand and Stellenbosch loam were probably caused by weathering and decay of the straw mulch due to the exceptionally wet conditions during the first half of the 1996/97-season. There is no realistic explanation for the low slope value of 0,18 obtained for the Stellenbosch sand clay loam under the vertical trellis.

The variation in slopes of $\sum E_s$ *versus* $\sum ET_o$ between the six mulched soils as shown in Table 6.6 could not be explained by variations in soil texture, bulk density or saturated hydraulic conductivity. Furthermore, it is to be expected that the presence of a mulch would negate the effect of these soil parameters on variance in evaporation losses.

Since mulch thickness can influence the slope of $\sum E_s$ *versus* $\sum ET_o$ (Van Zyl & Myburgh, 1997), the results obtained in this study will not be applicable to situations where mulch thickness is higher or lower than 7,7 t ha^{-1}. Furthermore, intrinsic characteristics of materials used for mulching might also limit the extrapolation of these results to other situations (Van Huyssteen, Van Zyl & Koen, 1984; Jalota, 1993). The effect of mulch material and mulch thickness on evaporation needs to be investigated by further research.

6.4 CONCLUSIONS

Mini-lysimeters proved to be accurate for measuring evaporation losses. Unfortunately, there is no conclusive evidence that the evaporation from mini-lysimeters is a true representation of that from field soils. Due to finite column length, evaporation could be underestimated if mini-lysimeters are used for periods longer than two weeks. Under wet soil conditions evaporation from unmulched soil could be higher in the middle section of the work row. Hence, to obtain accurate evaporation measurements, this variation should be considered in future research.

Evaporation from unmulched, untilled soil could be estimated with acceptable accuracy by using the Boesten & Stroosnijder (1986) model. Since this model was initially developed for bare, fallow soils, some adaptions were necessary to account for canopy effects. Due to canopy shading effects, $\sum E_s$ was not equal to $\sum ET_o$ during stage one evaporation. During stage two evaporation, β-values tended to be higher under a horizontal trellis in comparison to a vertical trellis. Furthermore, β-values differed between the six soil types used in this study. Beta-values tended to decrease with an increase in clay or silt content and, therefore, increase with an increase in total sand content. However, due to outlier values these parameters were not reliable to predict variation in β-values. Beta-values increased with an increase in saturated hydraulic conductivity, but again, an outlier value rendered this parameter unsuitable for estimation of β. Unsaturated hydraulic conductivity would probably be the best parameter to explain variation in evaporation behaviour between the different soil types and should be investigated by further research.

Mulching reduced evaporation losses significantly under relatively wet soil conditions. For most soils there were no difference between evaporation from bare soil and mulched soil ten days after irrigation. Cumulative evaporation from mulched soil correlated linearly with cumulative reference crop evapotranspiration for up to three weeks after irrigation. Hence, different stages could not be distinguished as in the case of evaporation from unmulched soil. $\sum E_s$ generally amounted to 30 % of $\sum ET_o$. This ratio, however, could be changed by mulch thickness, mulch material and loosening of the surface by tillage. These effects should also be addressed by further research.

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TABLE 6.1

List of soil forms of which the topsoil was sampled at various localities to study the effect of soil texture, surface condition and canopy orientation on evaporation losses from vineyard soils in a mini-lysimeter field trail at Stellenbosch.

Treatment number	Locality	Soil form	Surface condition	Trellis system	Season
T1	De Doorns	Fernwood	Bare	1,5 m Slanting trellis	1993/94
T2				Perold	1994/95
T3			Mulched	1,5 m Slanting trellis	1993/94
T4				Perold	1994/95
T5	Robertson	Garies	Bare	1,5 m Slanting trellis	1993/94
T6				Perold	1994/95
T7			Mulched	1,5 m Slanting trellis	1993/94
T8				Perold	1994/95
T9	Stellenbosch	Glenrosa	Bare	1,5 m Slanting trellis	1994/95
T10				Perold	1995/96
T11			Mulched	1,5 m Slanting trellis	1994/95
T12				Perold	1995/96
T13	Upington	Dundee	Bare	1,5 m Slanting trellis	1994/95
T14				Perold	1995/96
T15			Mulched	1,5 m Slanting trellis	1994/95
T16				Perold	1995/96
T17	Upington	Plooysburg	Bare	1,5 m Slanting trellis	1995/96
T18				Perold	1996/97
T19			Mulched	1,5 m Slanting trellis	1995/96
T20				Perold	1996/97
T21	Stellenbosch	Clovelly	Bare	1,5 m Slanting trellis	1995/96
T22				Perold	1996/97
T23			Mulched	1,5 m Slanting trellis	1995/96
T24				Perold	1996/97

TABLE 6.2

Pan coefficient (K_p) for Class-A pan for different groundcover,levels of mean relative humidity and daily windrun (Doorenbos & Pruitt, 1977).

	Case A : Pan placed in short green cropped area				Case B* : Pan placed in dry fallow area			
Windrun (km d^{-1})	Windward side distance of green crop (m)	Mean relative humidity (%)			Windward side distance of dry fallow (m)	Mean relative humidity (%)		
		Low (< 40)	Medium (40-70)	High (> 70)		Low (< 40)	Medium (40-70)	High (> 70)
Light (< 175)	1	0,55	0,65	0,75	1	0,70	0,80	0,85
	10	0,65	0,75	0,85	10	0,60	0,70	0,80
	100	0,70	0,80	0,85	100	0,55	0,65	0,75
	1 000	0,75	0,85	0,85	1 000	0,50	0,60	0,70
Moderate (175 - 425)	1	0,50	0,60	0,65	1	0,65	0,75	0,80
	10	0,60	0,70	0,75	10	0,55	0,65	0,70
	100	0,65	0,75	0,80	100	0,50	0,60	0,65
	1 000	0,70	0,80	0,80	1 000	0,45	0,55	0,60
Strong (425 - 700)	1	0,45	0,50	0,60	1	0,60	0,65	0,70
	10	0,55	0,60	0,65	10	0,50	0,55	0,65
	100	0,60	0,65	0,70	100	0,45	0,50	0,60
	1 000	0,65	0,70	0,75	1 000	0,40	0,45	0,55
Very strong (> 700)	1	0,40	0,45	0,50	1	0,50	0,60	0,65
	10	0,45	0,55	0,60	10	0,45	0,50	0,55
	100	0,50	0,60	0,65	100	0,40	0,45	0,50
	1 000	0,55	0,60	0,65	1 000	0,35	0,40	0,45

* For extensive areas of bare-fallow soils and no agricultural development, reduce K_{pan} by 20 % under hot, windy conditions, by 5 - 10 % for moderate wind, temperature and humidity conditions.

TABLE 6.3

Locality, textural class and bulk density of six soils used to determine evaporation losses from vineyard soils in a mini-lysimeter field trial at Stellenbosch.

Locality	Depth (mm)	Soil texture						Textural class	Bulk density (Mg m^{-3})
		Clay (%)	Silt (%)	Sand fraction (%)			Gravel* (%)		
				Fine	Medium	Coarse			
De Doorns	0 - 150	2,41	1,78	35,89	38,88	21,78	0	coarse sand	1,569
	150 - 300	2,01	0,64	30,81	42,37	23,67	0	coarse sand	1,649
Robertson	0 - 150	12,63	16,33	63,57	7,88	1,98	0	fine sand loam	1,509
	150 - 300	12,68	14,69	61,81	8,95	1,95	0	fine sand loam	1,631
Stellenbosch	0 - 150	19,18	25,81	14,10	7,02	36,99	47,1	coarse sand clay loam	1,547
	150 - 300	23,71	27,39	14,50	8,01	29,04	47,1	coarse sand clay loam	1,778
Upington	0 - 150	10,17	27,12	64,51	0,94	0,47	0	fine sand loam	1,454
	150 - 300	10,19	29,08	60,52	2,16	0,59	0	fine sand loam	1,592
Upington	0 - 150	3,20	9,20	60,35	10,46	17,08	0	fine sand	1,626
	150 - 300	3,21	8,81	64,42	10,06	13,76	0	fine sand	1,657
Stellenbosch	0 - 150	23,15	31,22	37,54	5,81	2,62	0	loam	1,394
	150 - 300	25,15	31,42	35,68	5,64	2,62	0	loam	1,529

* Particle size analysis was done on soil fraction < 2,0 mm after gravel had been removed by sieving.

TABLE 6.4

Seasonal variation in slope of cumulative evaporation *vs* cumulative reference crop evapotranspiration curve during stage one evaporation as determined for six soil types under two grapevine canopy orientations in a mini-lysimeter field trial at Stellenbosch.

Soil texture	Canopy orientation	Variation in slope over the growing season							
		Sep.	Oct.	Nov.	Des.	Jan.	Feb.	Mar.	Apr.
Coarse sand (*De Doorns*)	Horizontal	1,00	0,94	0,85	0,97	0,87	0,90	0,97	0,91
	Vertical	1,00	0,98	0,79	0,71	0,95	0,91	0,97	0,97
Fine sand loam (*Robertson*)	Horizontal	1,00	1,00	0,95	0,87	0,69	0,98	0,88	0,83
	Vertical	1,00	1,00	1,00	0,61	0,74	0,69	0,84	0,90
Coarse sand clay loam (*Stellenbosch*)	Horizontal	*	*	*	*	*	*	*	*
	Vertical	*	*	*	*	*	*	*	*
Fine sand loam (*Upington*)	Horizontal	0,93	0,99	0,92	0,79	0,92	0,74	0,81	0,97
	Vertical	0,96	0,77	0,85	0,92	0,93	0,88	1,00	-
Fine sand (*Upington*)	Horizontal	1,00	-	0,87	0,63	1,00	0,95	1,00	0,93
	Vertical	1,00	1,00	-	-	0,88	0,88	0,88	0,92
Loam (*Stellenbosch*)	Horizontal	1,00	0,85	-	0,73	1,00	0,86	0,89	0,89
	Vertical	0,87	0,98	-	-	0,97	0,84	0,90	0,97
Mean	**Horizontal**	**0,99**	**0,95**	**0,89**	**0,80**	**0,90**	**0,89**	**0,91**	**0,91**
	Vertical	**0,97**	**0,94**	**0,88**	**0,77**	**0,89**	**0,84**	**0,92**	**0,94**

* Stage one evaporation lasted less than one day and could not be assessed by means of daily evaporation measurements.

TABLE 6.5

Mean β-Values for six soil types from different localities as determined by means of mini-lysimeters under two grapevine canopy surface orientations during various drying cycles as applied over the growing season.

Soil texture (*locality*)	Canopy surface orientation	Number of drying clycles	β-value ($mm^{0,5}$)	Standard error
Coarse sand (*De Doorns*)	Horizontal Vertical	16 14	4,68 4,18	0,14 0,13
Fine sand loam (*Robertson*)	Horizontal Vertical	11 11	3,50 2,93	0,20 0,14
Coarse sand clay loam (*Stellenbosch*)	Horizontal Vertical	15 7	2,15 2,31	0,09 0,15
Fine sand loam (*Upington*)	Horizontal Vertical	15 7	3,71 3,56	0,12 0,15
Fine sand (*Upington*)	Horizontal Vertical	7 7	4,19 3,36	0,12 0,14
Loam (*Stellenbosch*)	Horizontal Vertical	7 7	3,95 3,80	0,22 0,15

TABLE 6.6

Mean slope of cumulative evaporation from the soil *vs* cumulative reference crop evapotranspiration for six mulched soil types from different localities determined by means of mini-lysimeters under two grapevine canopy surface orientations during a number of drying cycles as applied over the growing season.

Soil texture (*locality*)	Canopy surface orientation	Number of drying cycles	Slope	Standard error
Coarse sand (*De Doorns*)	Horizontal Vertical	13 12	0,25 0,26	0,012 0,010
Fine sand loam (*Robertson*)	Horizontal Vertical	7 7	0,30 0,29	0,016 0,013
Coarse sand clay loam (*Stellenbosch*)	Horizontal Vertical	12 7	0,27 0,18	0,012 0,015
Fine sand loam (*Upington*)	Horizontal Vertical	12 7	0,35 0,32	0,024 0,026
Fine sand (*Upington*)	Horizontal Vertical	7 7	0,26 0,40	0,022 0,021
Loam (*Stellenbosch*)	Horizontal Vertical	7 7	0,27 0,44	0,019 0,016

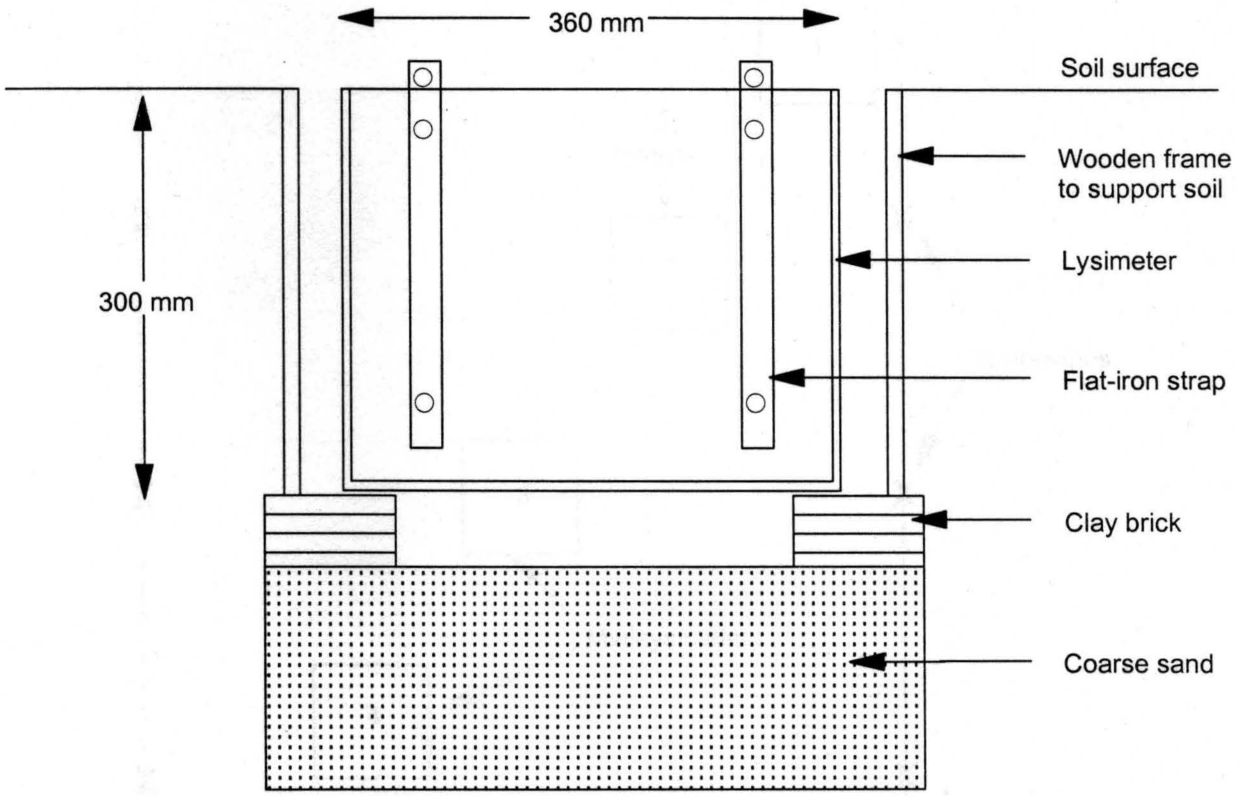


Figure 6.1. Diagram showing construction and installation of a mini-lysimeter.

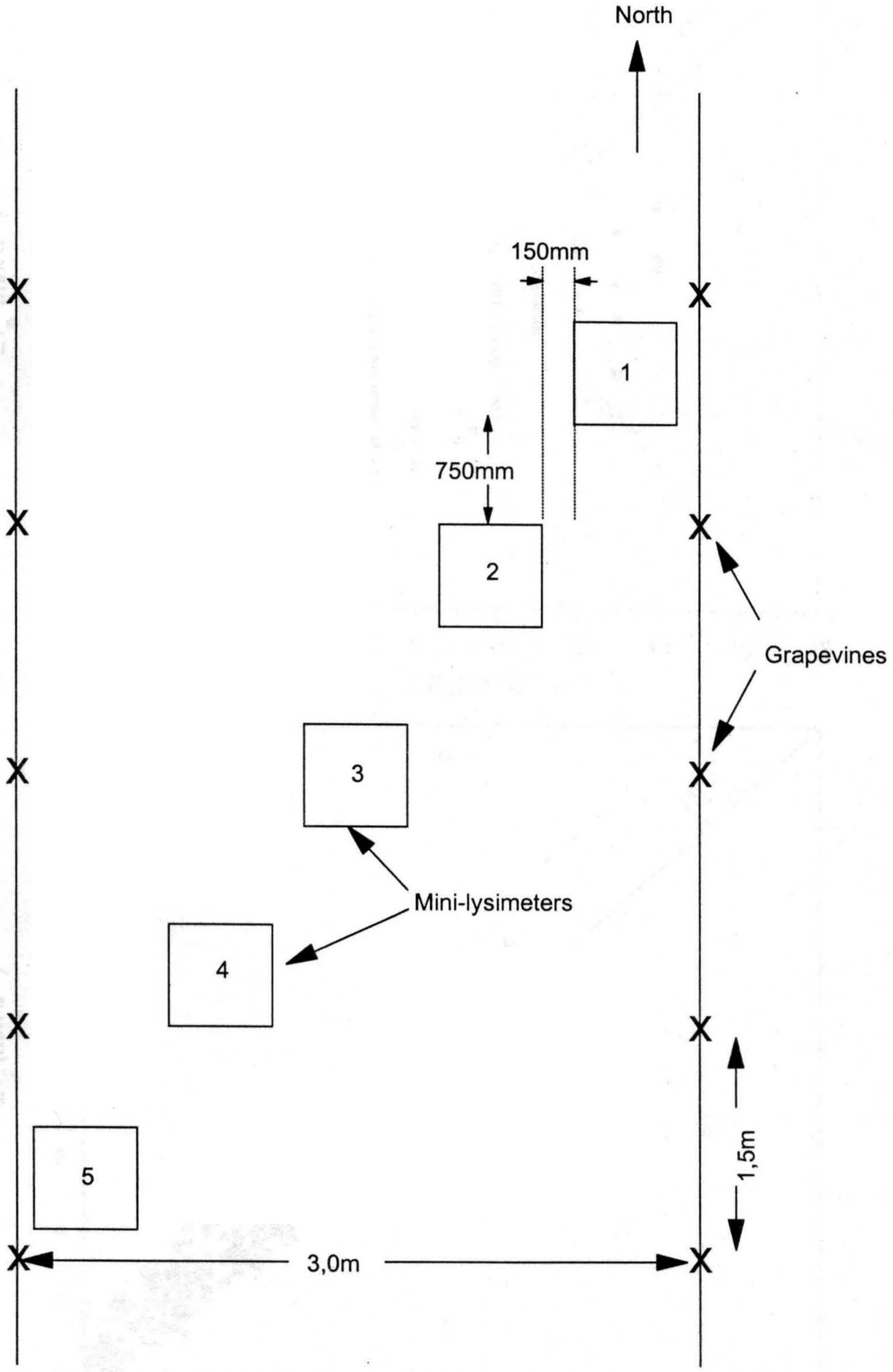


Figure 6.2. Experimental layout per soil type/surface treatment combination consisting of five mini-lysimeters installed diagonally across the inter row space.

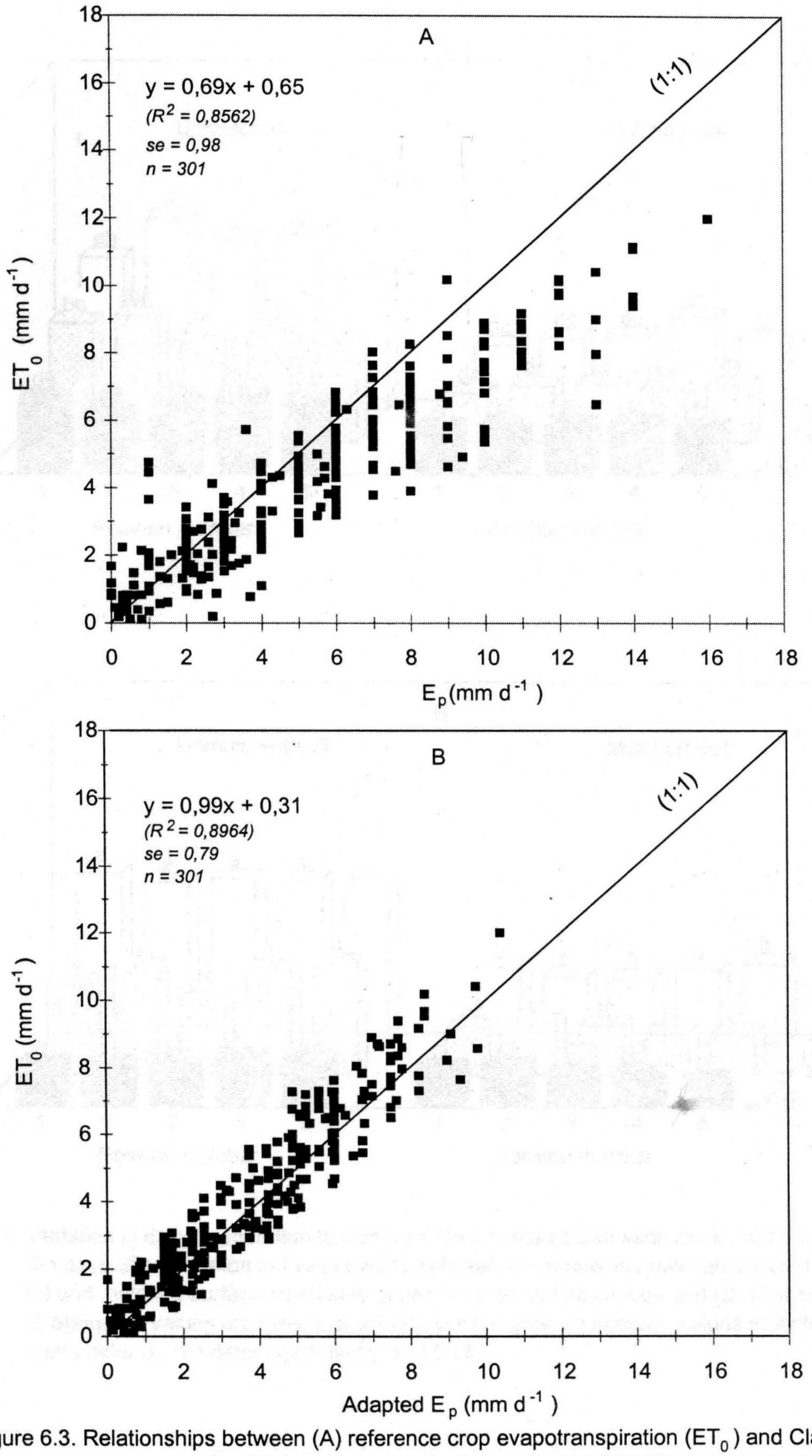


Figure 6.3. Relationships between (A) reference crop evapotranspiration (ET_0) and Class-A pan evaporation (E_p) measured at Stellenbosch and (B) ET_0 and adapted Class-A pan evaporation as proposed by Doorenbos & Pruitt (1977) for the same data.

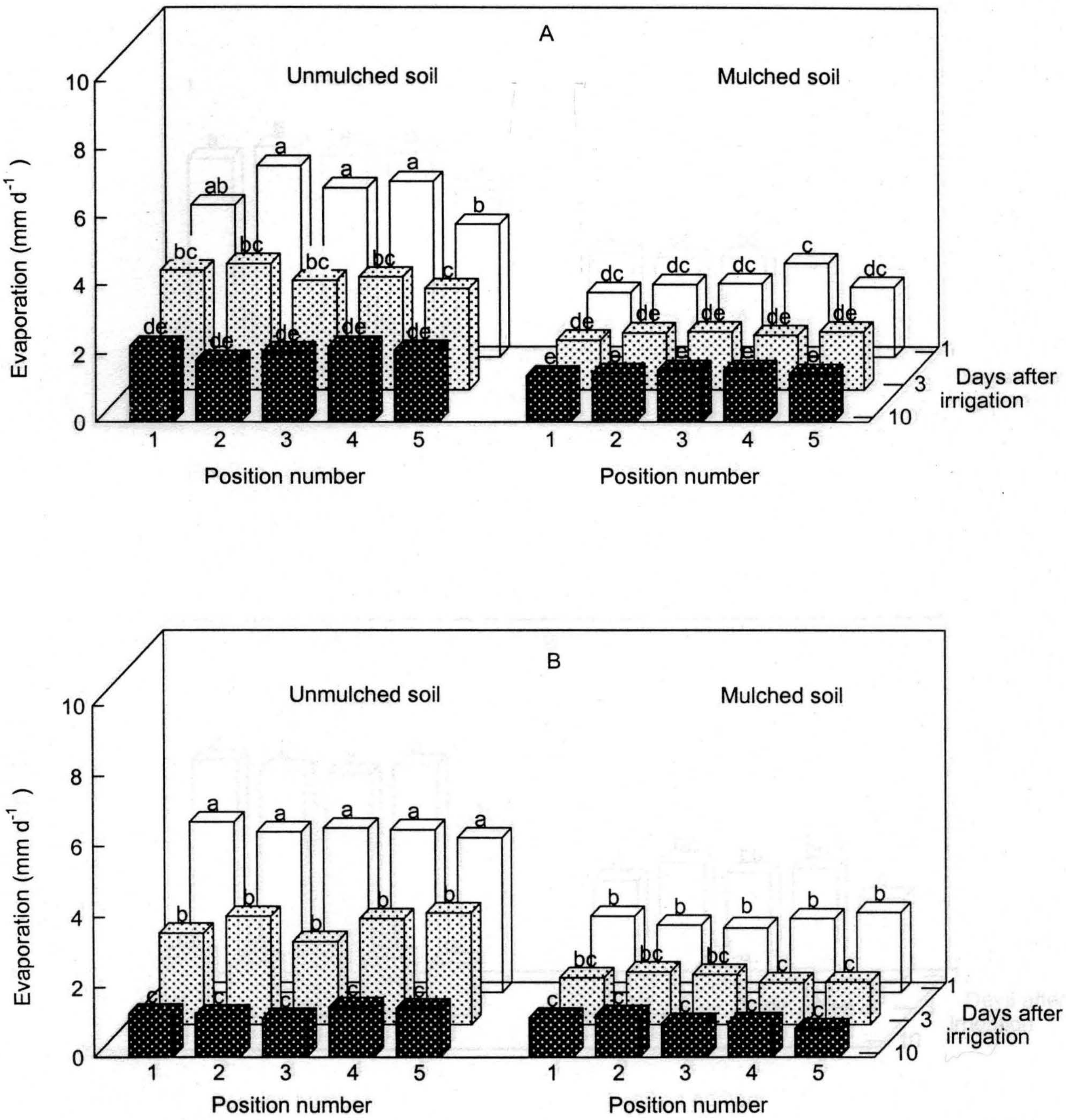
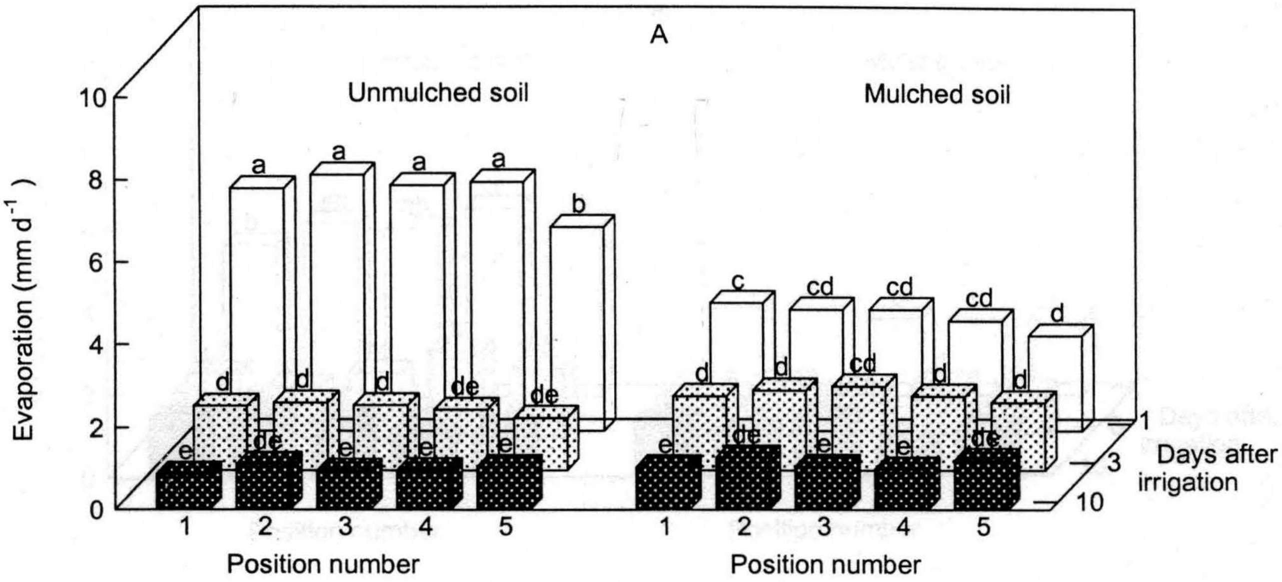


Figure 6.4. Variation in daily evaporation losses from De Doorns coarse sand measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly ($P \leq 0,05$).



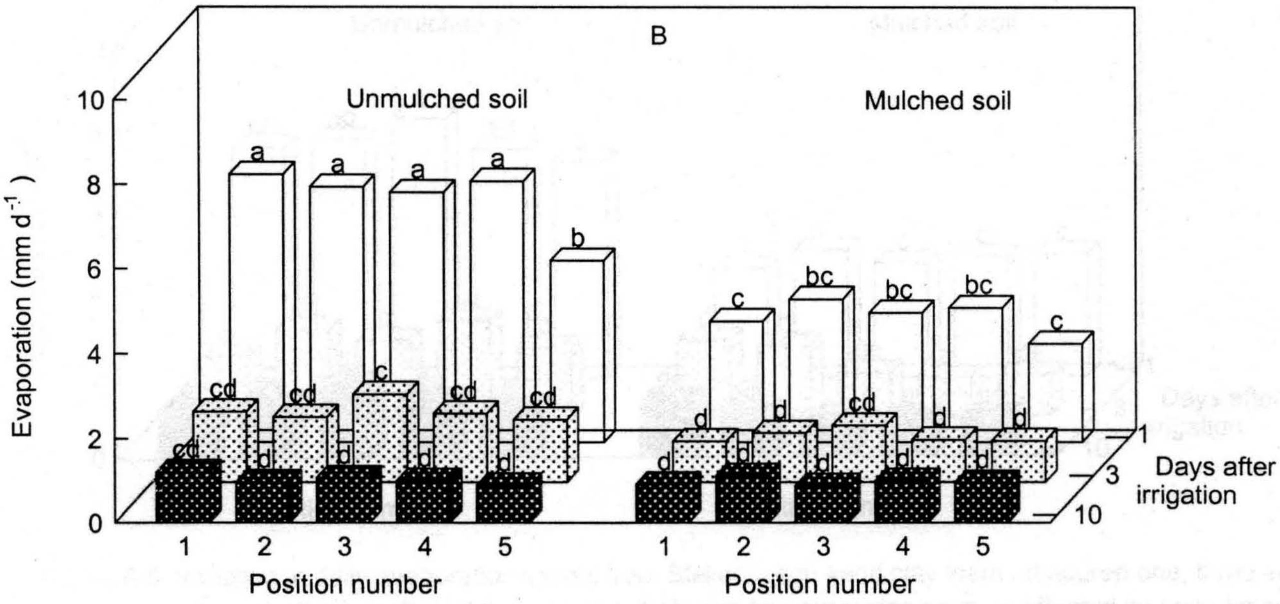


Figure 6.5. Variation in daily evaporation losses from Robertson sand loam measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly ($P \leq 0,05$).

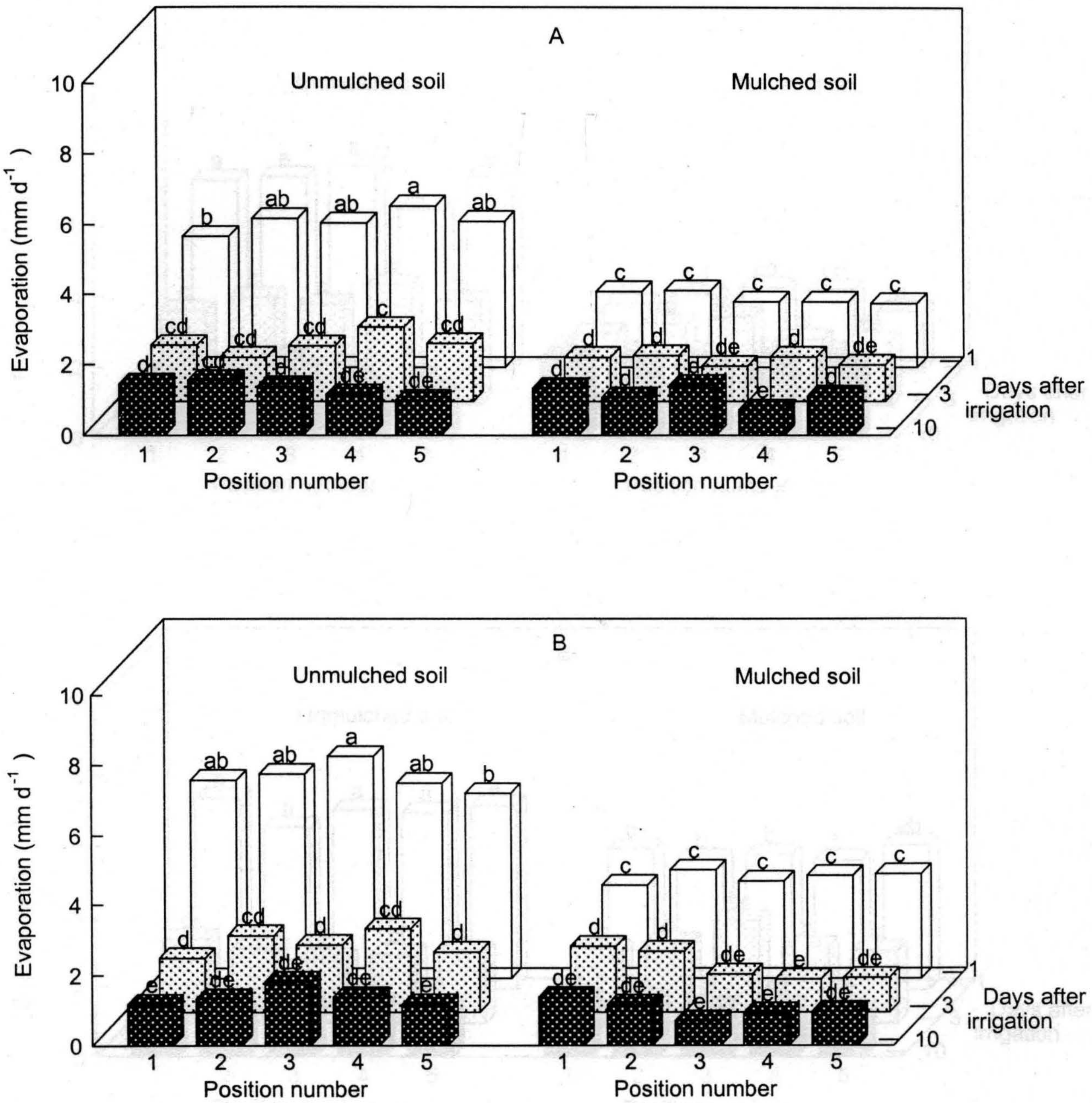


Figure 6.6. Variation in daily evaporation losses from Stellenbosch sand clay loam measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly ($P \leq 0,05$).

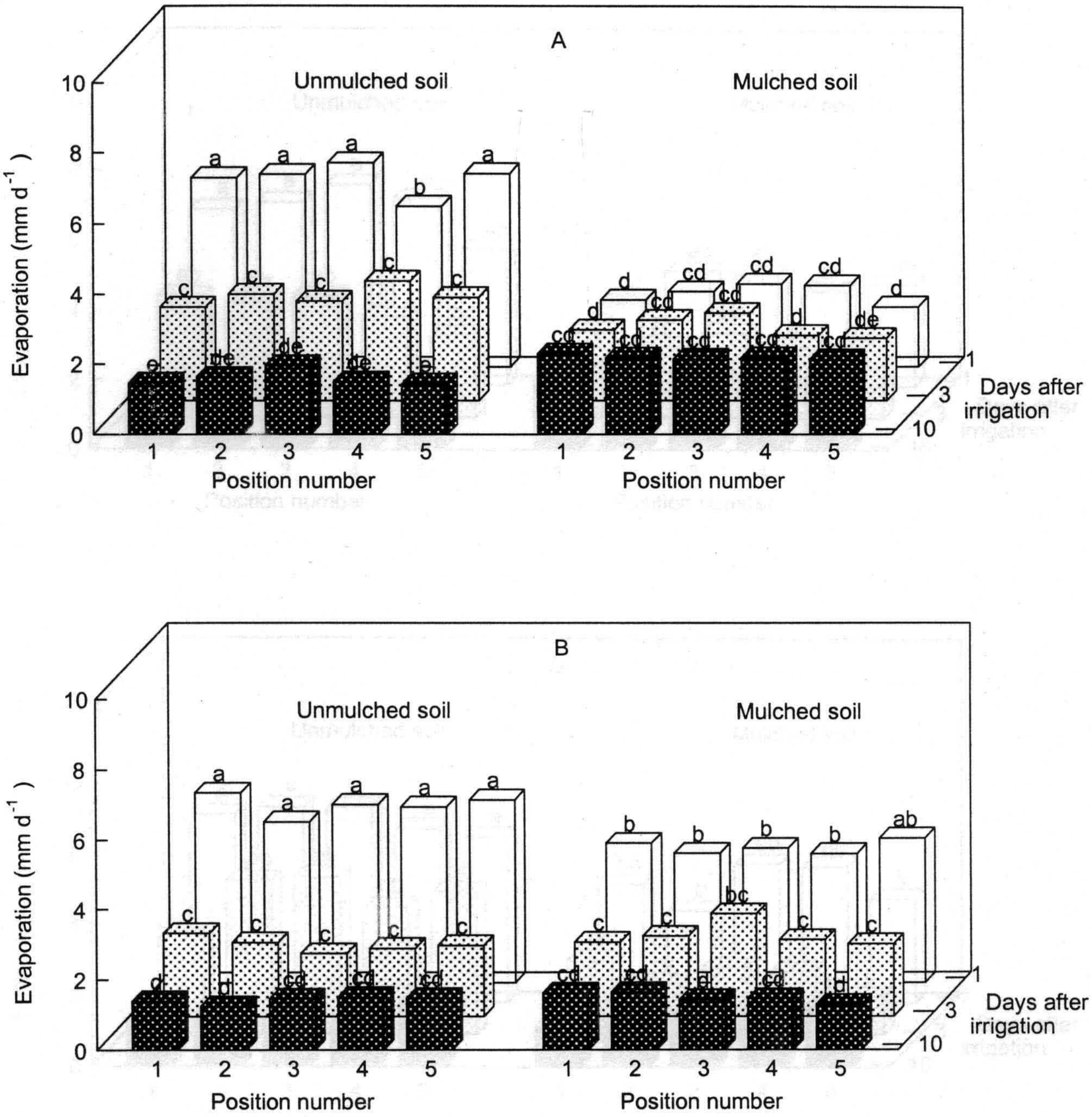


Figure 6.7. Variation in daily evaporation losses from Upington sand loam measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly ($P \leq 0,05$).

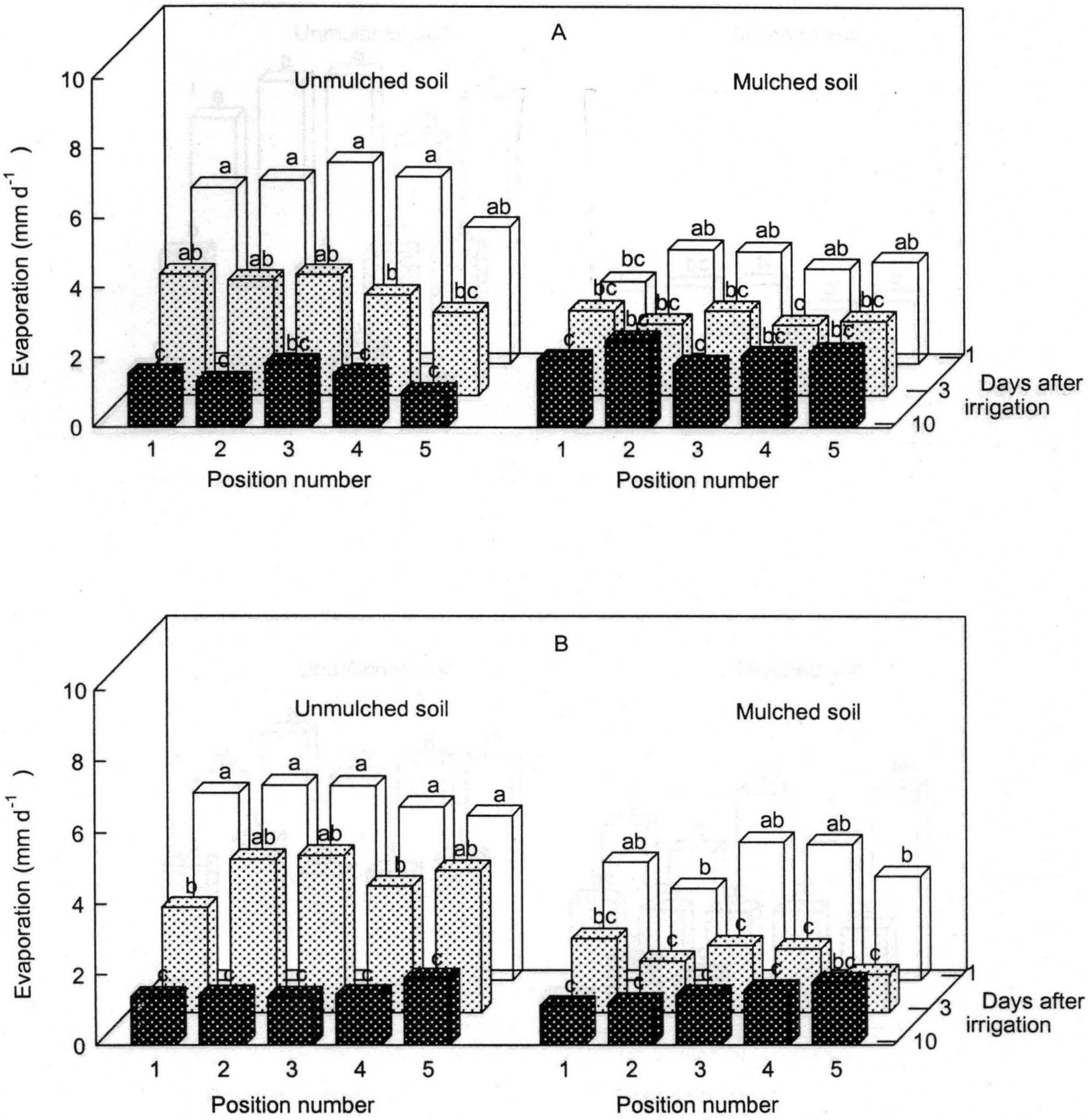
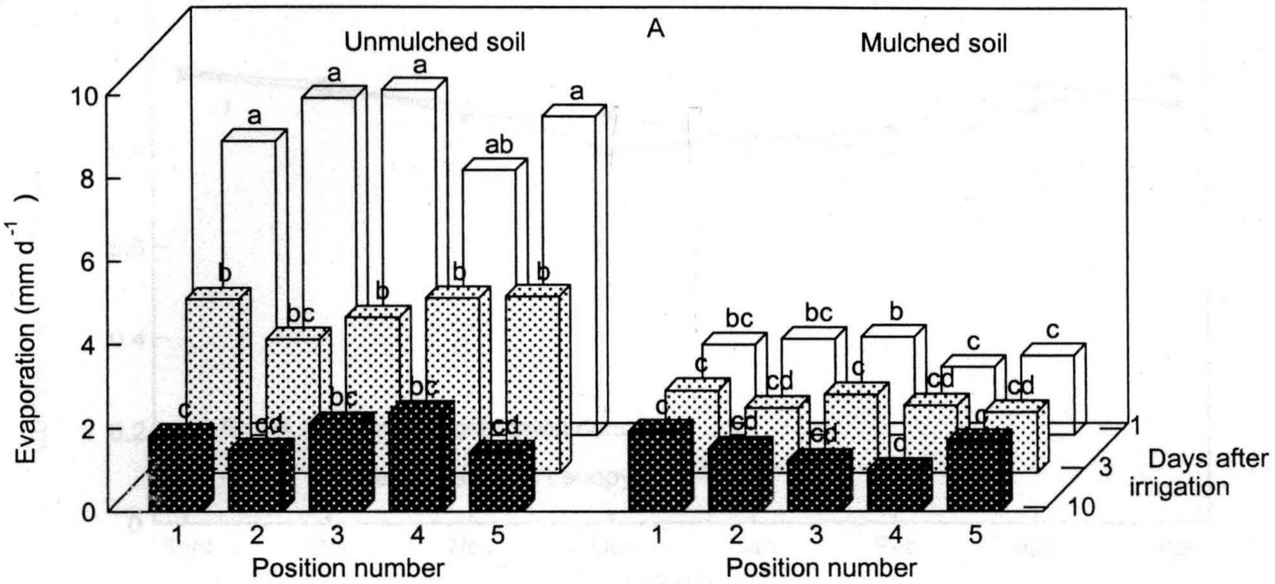


Figure 6.8. Variation in daily evaporation losses from Upington sand measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly ($P \leq 0,05$).



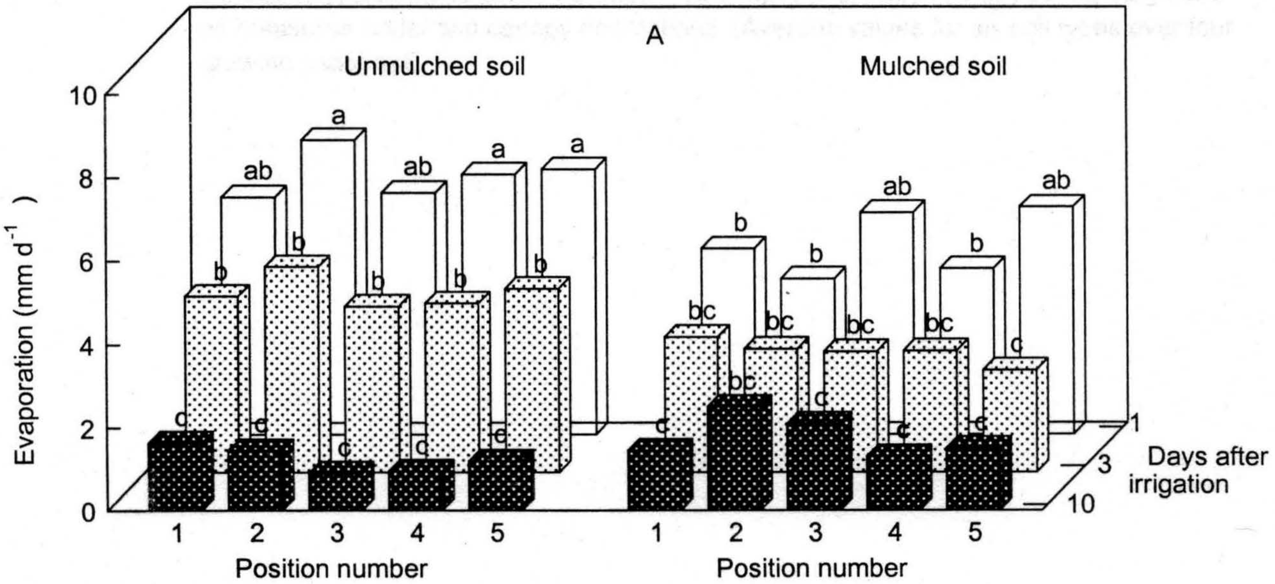


Figure 6.9. Variation in daily evaporation losses from Stellenbosch loam measured one, three and ten days after irrigation at five positions between two grapevine rows as affected by unmulched and mulched surface conditions under (A) a horizontal canopy and (B) a vertical canopy. Evaporation values are means obtained over the growing season. Values identified by the same letter do not differ significantly (P ≤ 0,05).

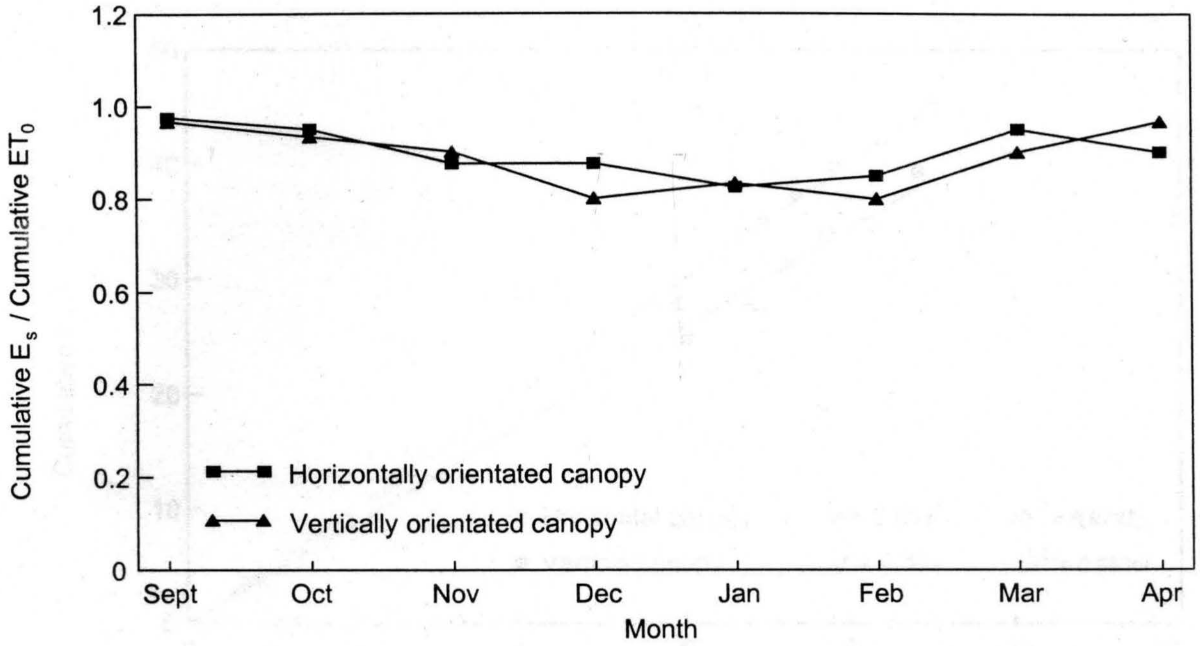


Figure 6.10. Seasonal variation in relationship between cumulative evaporation from unmulched soil surface (E_s) and cumulative reference crop evapotranspiration (ET_0) during stage one as measured under two canopy orientations. (Average values for six soil types over four growing seasons).

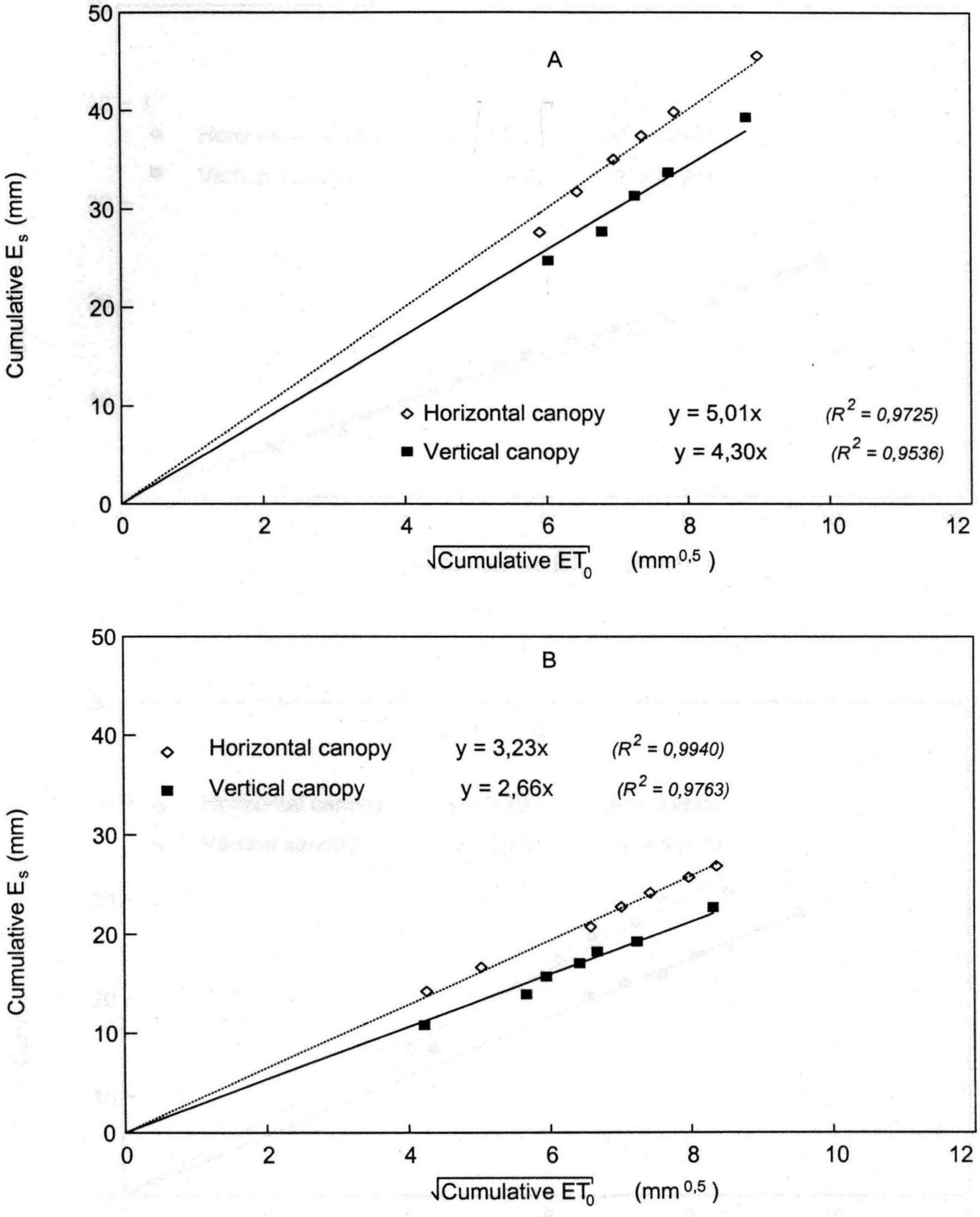


Figure 6.11. Examples of cumulative E_s *versus* square root of cumulative ET_0 plots to determine beta-values (= slope of curves) for (A) De Doorns sand and (B) Robertson sand loam under two canopy orientations.

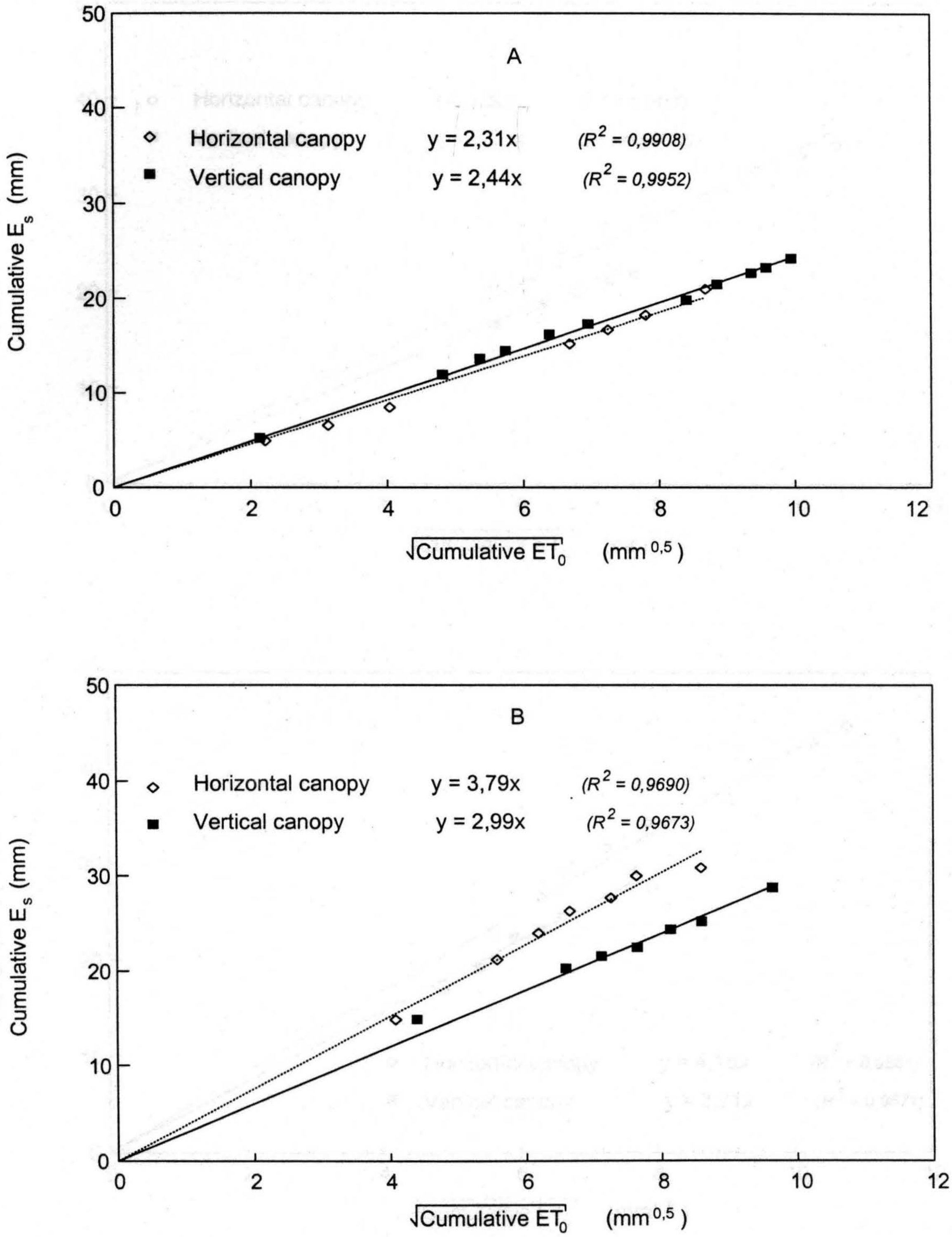


Figure 6.12. Examples of cumulative E_s *versus* square root of cumulative ET_0 plots to determine beta-values (= slope of curves) for (A) Stellenbosch sand clay loam and (B) Upington fine sand loam under two canopy orientations.

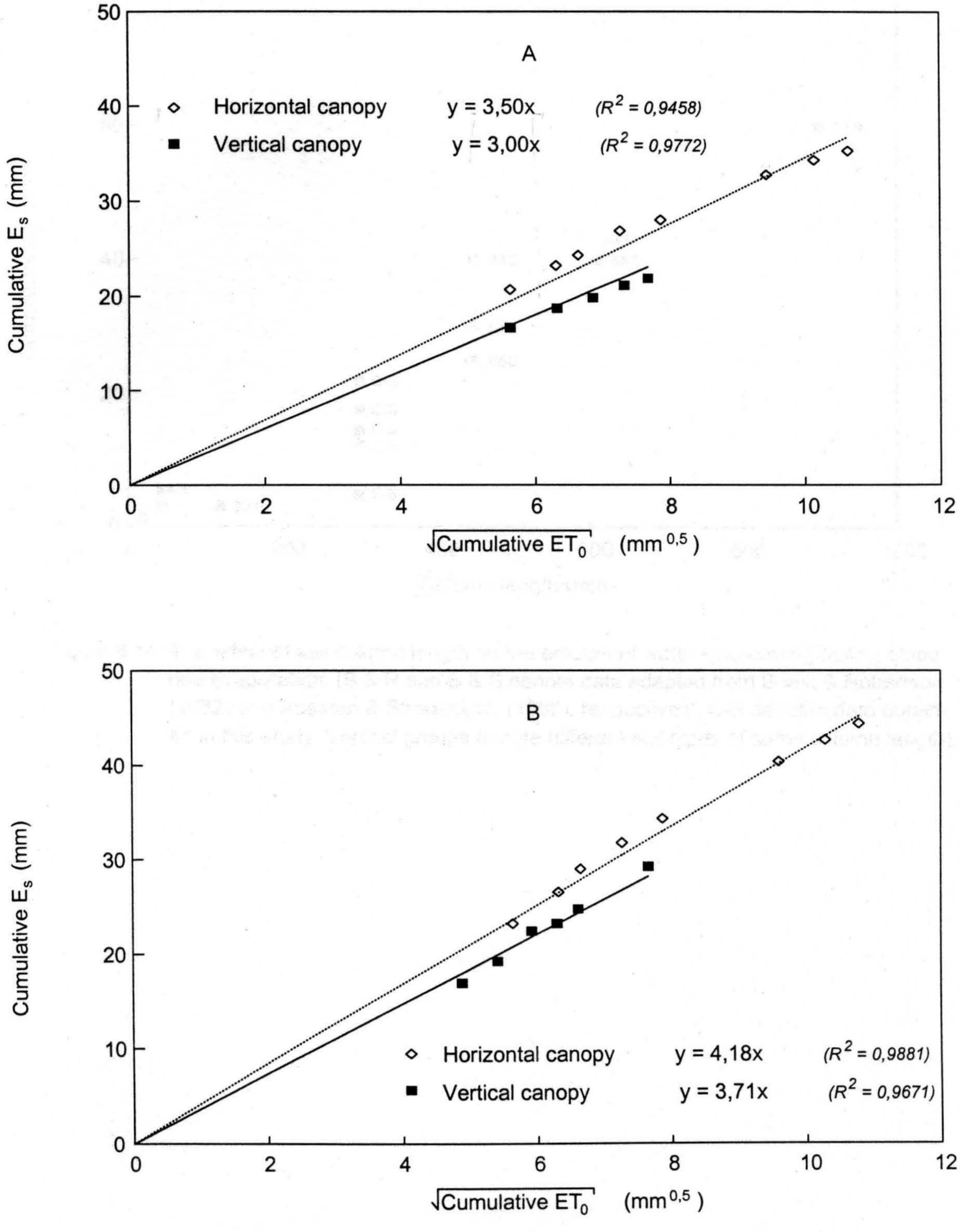


Figure 6.13. Examples of cumulative E_s *versus* square root of cumulative ET_0 plots to determine beta-values (= slope of curves) for (A) Upington fine sand and (B) Stellenbosch loam under two canopy orientations.

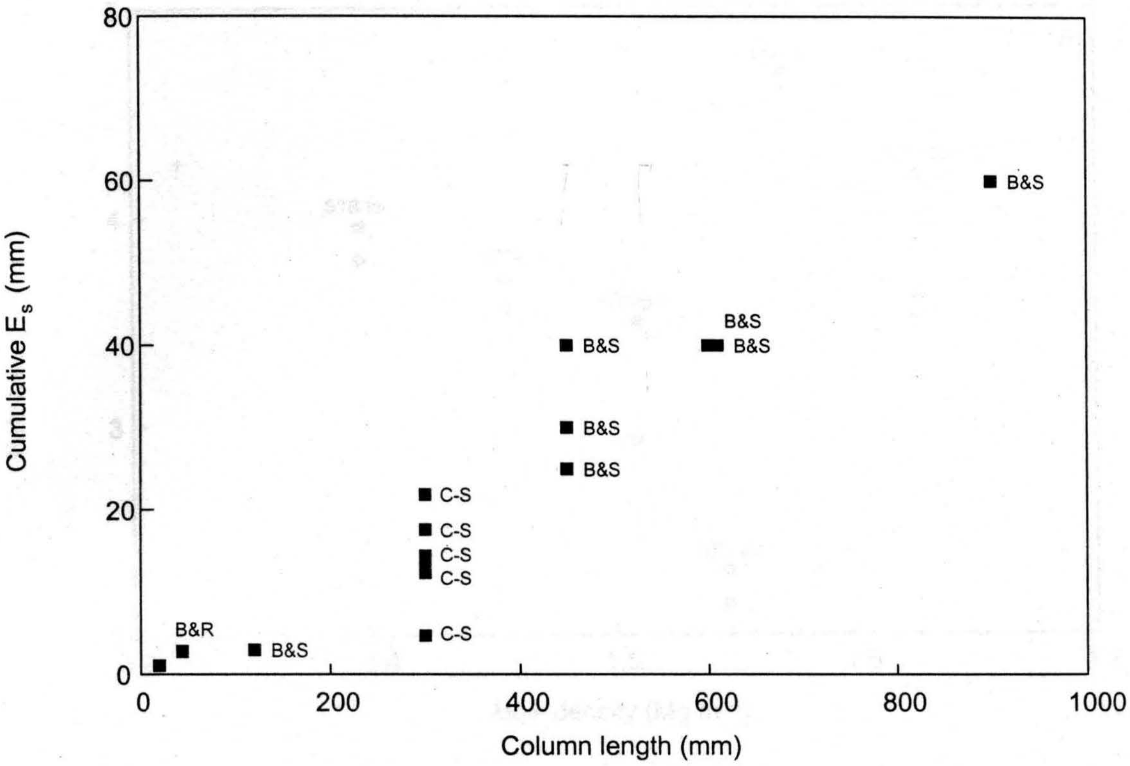


Figure 6.14. The effect of soil column length on the amount of water evaporating during stage one evaporation. (B & R and B & S denote data adapted from Boast & Robertson (1982) and Boesten & Stroosnijder (1986), respectively. C-S denotes data obtained in this study. Vertical groups denote different soil types of same column length).

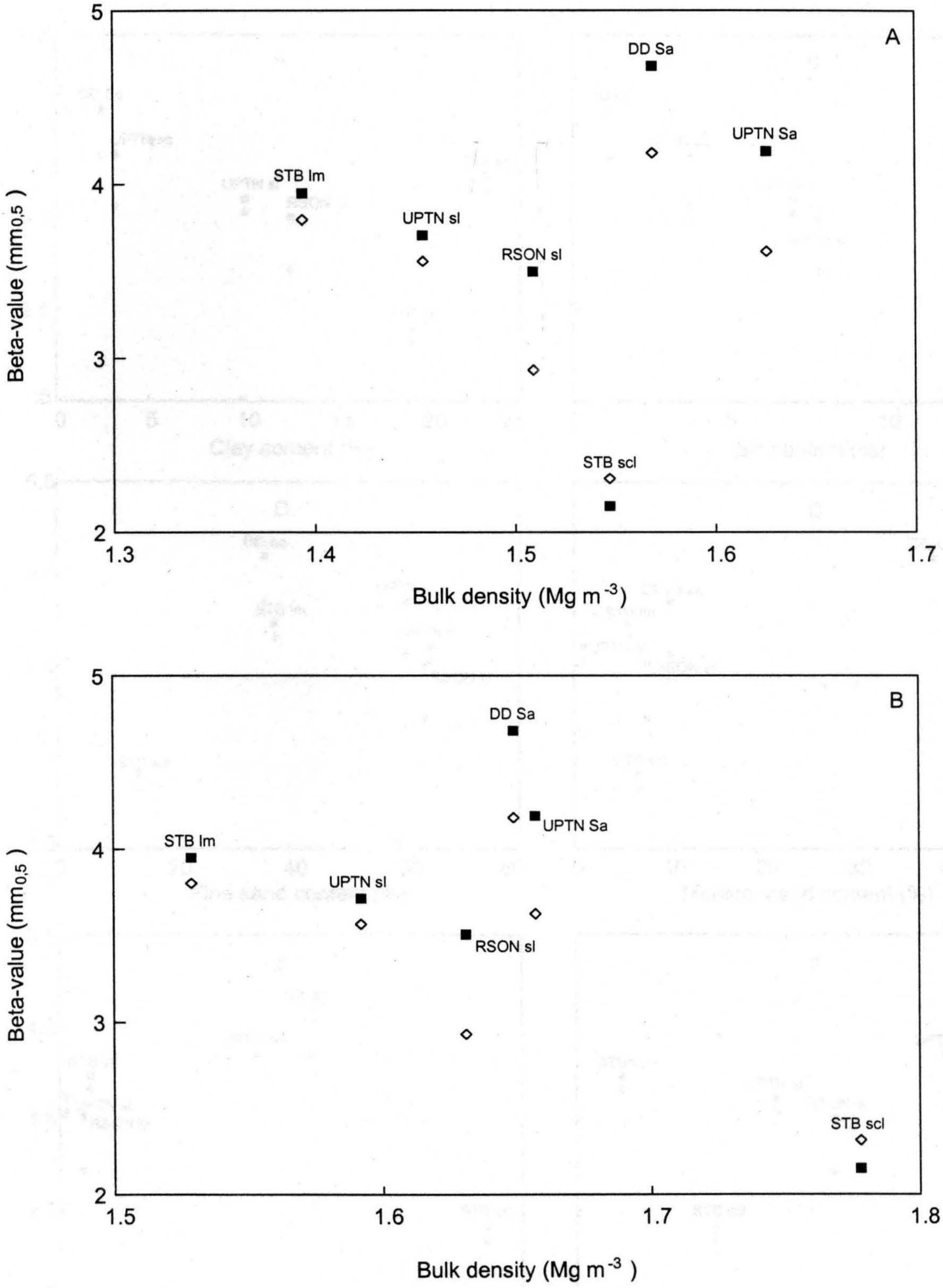


Figure 6.15. Relationship between beta-values and soil bulk density of (A) 0 to 150 mm depth layer, and (B) 150 to 300 mm depth layer for six different soil types where, DD sa = De Doorns coarse sand, STB scl = Stellenbosch coarse sand clay loam, RSON sl = Robertson fine sand loam, STB lm = Stellenbosch loam, UPTN sl = Upington fine sand loam and UPTN sa = Upington fine sand. (■ and ◇ denote values obtained under horizontal and vertical canopies, respectively).

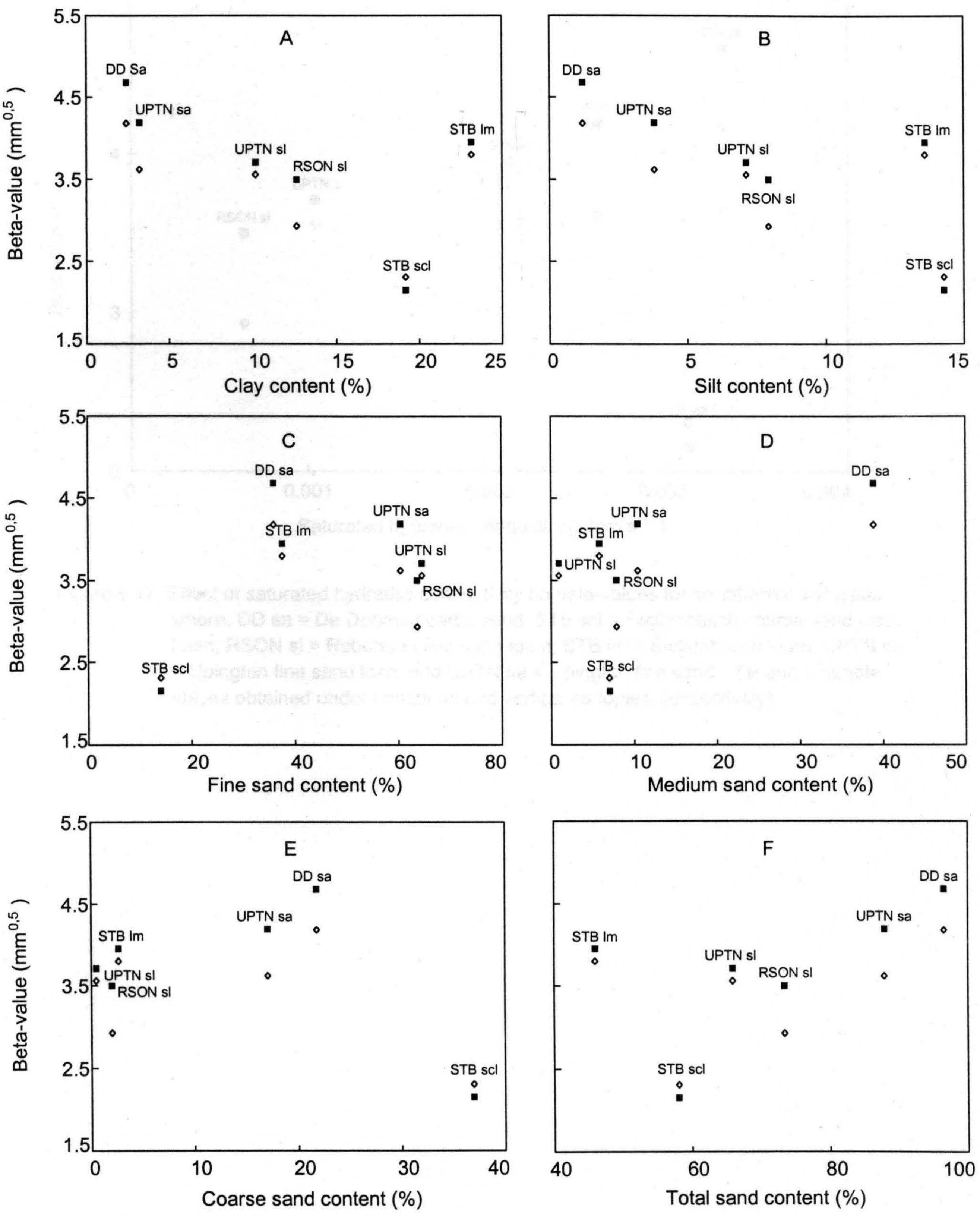


Figure 6.16. Relationship between beta-values and soil textural classes for six different soil types where, DD sa = De Doorns coarse sand, STB scl = Stellenbosch coarse sand clay loam, RSON sl = Robertson fine sand loam, STB lm = Stellenbosch loam, UPTN sl = Upington fine sand loam and UPTN sa = Upington fine sand. (■ and ◇ denote values obtained under horizontal and vertical canopies, respectively).

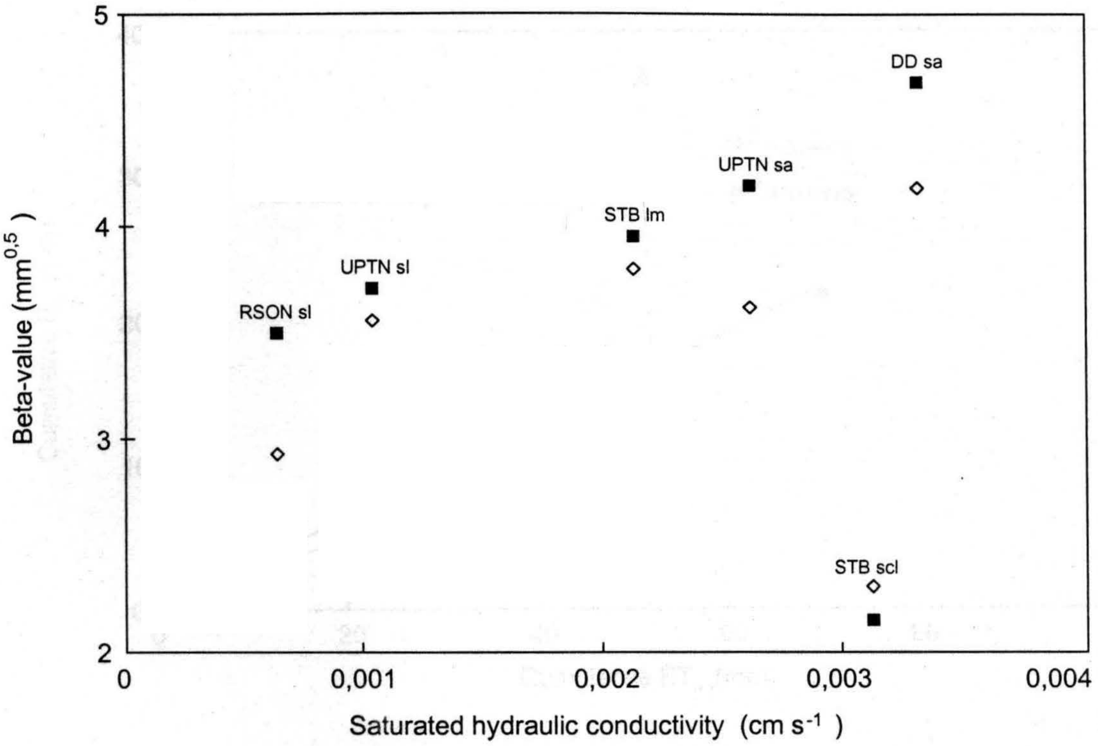
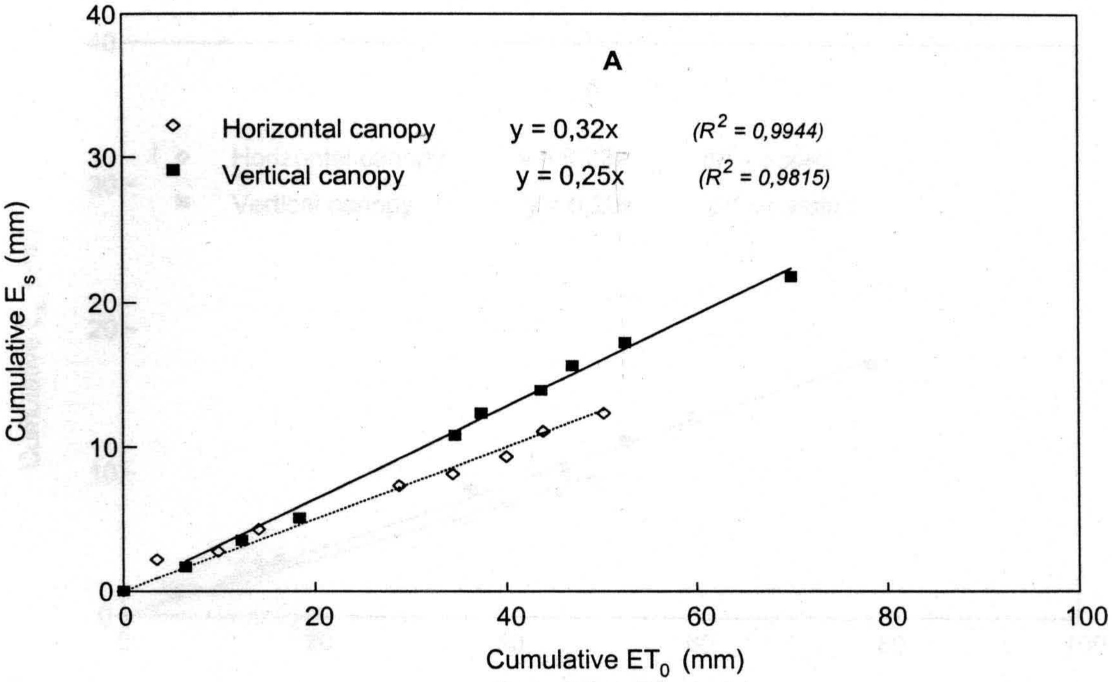


Figure 6.17. Effect of saturated hydraulic conductivity on beta-values for six different soil types where, DD sa = De Doorns coarse sand, STB scl = Stellenbosch coarse sand clay loam, RSON sl = Robertson fine sand loam, STB lm = Stellenbosch loam, UPTN sl = Upington fine sand loam and UPTN sa = Upington fine sand. (■ and ◇ denote values obtained under horizontal and vertical canopies, respectively).



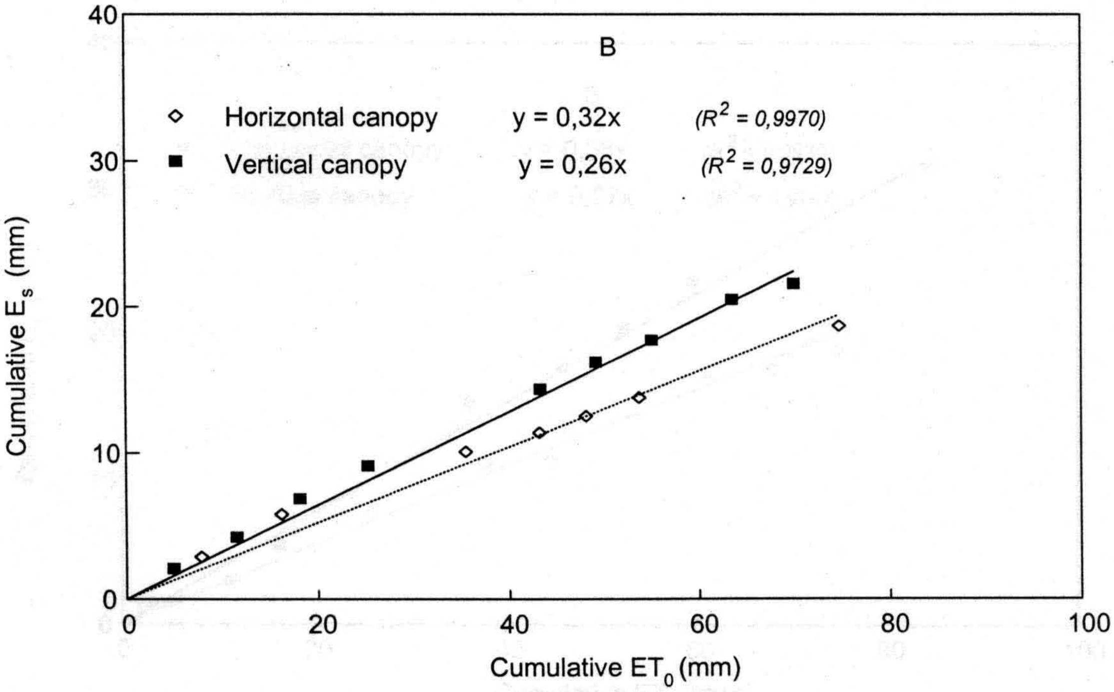


Figure 6.18. Examples of relationship between cumulative E_s and cumulative ET_0 for (A) mulched De Doorns sand and (B) mulched Robertson sand loam under two canopy orientations.

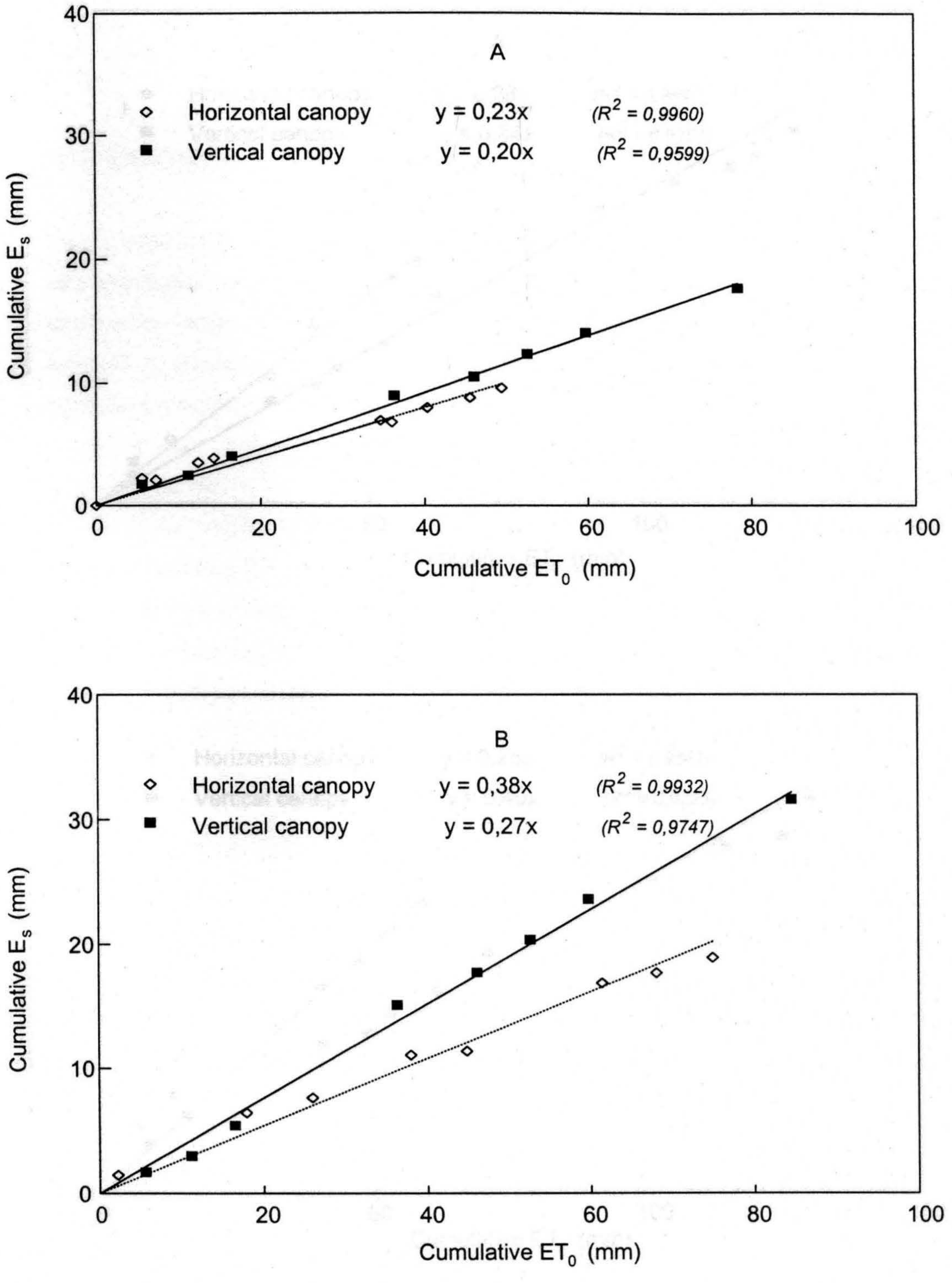
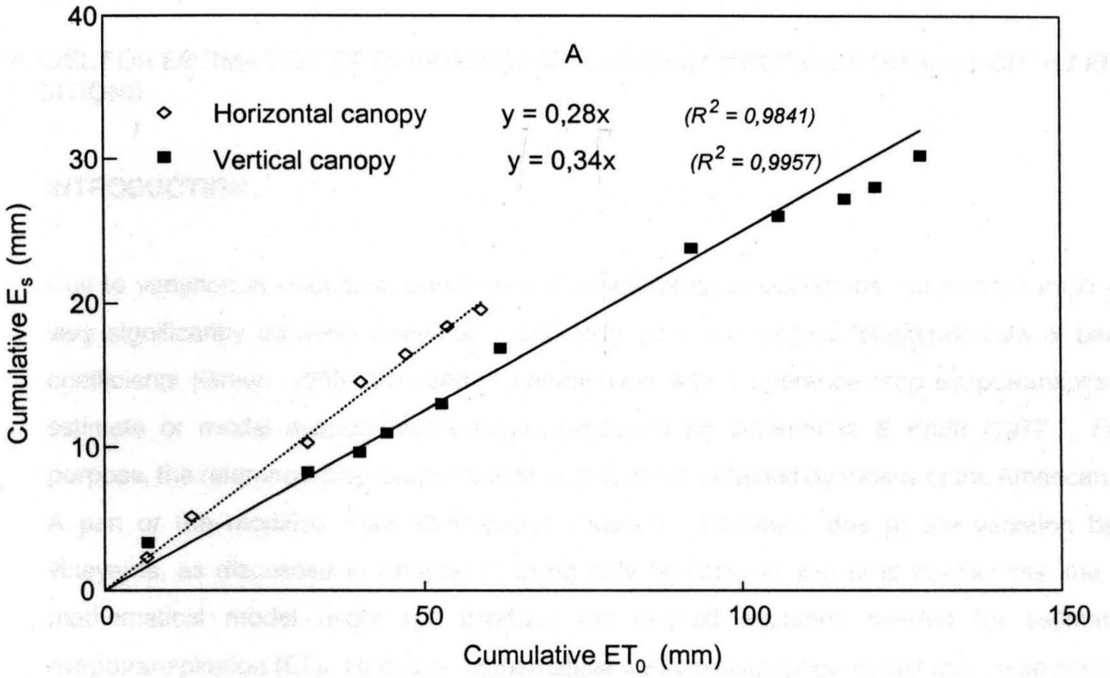


Figure 6.19. Examples of relationship between cumulative E_s and cumulative ET_0 for (A) mulched Stellenbosch sand clay loam and (B) mulched Upington sand loam under two canopy orientations.



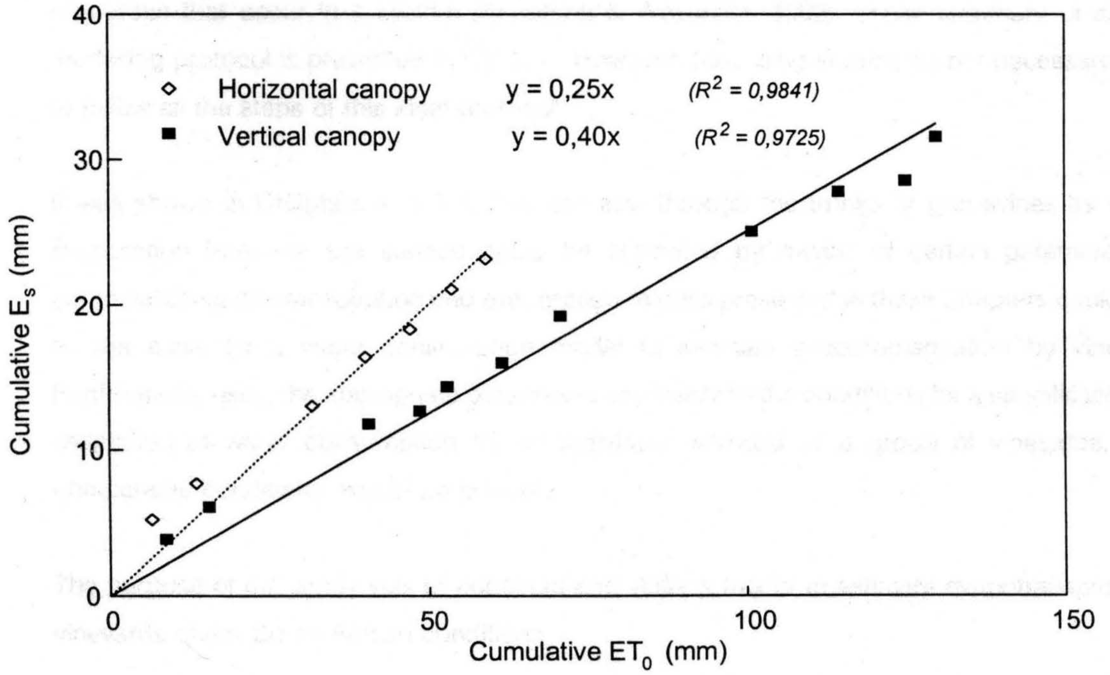


Figure 6.20. Examples of relationship between cumulative E_s and cumulative ET_0 for (A) mulched Upington sand, and (B) mulched Stellenbosch loam under two canopy orientations.

CHAPTER 7

A MODEL FOR ESTIMATION OF EVAPOTRANSPIRATION IN VINEYARDS UNDER SOUTH AFRICAN CONDITIONS

7.1 INTRODUCTION

Due to variation in viticultural practices and meteorological conditions, water consumption may vary significantly between vineyards. Generally, only one or two "standard" sets of pan crop coefficients (Green, 1985) are used in combination with a reference crop evapotranspiration to estimate or model evapotranspiration as proposed by Doorenbos & Pruitt (1977). For this purpose, the reference crop evapotranspiration is either obtained by means of the American Class-A pan or the modified Penman-Monteith equation. However, due to the variation between vineyards, as discussed in Chapter 1, using only two sets of pan crop coefficients, the simple mathematical model might not produce the desired accuracy needed for estimation of evapotranspiration (ET). Hence, a mathematical water consumption model that could account for these variations would improve estimation of ET. In this regard a model can be defined as a mathematical simulation of physical processes by means of equations describing the physical processes that occur in a system (Anderson & Woessner, 1992). Their summary of an ideal modelling protocol is presented in Fig. 7.1. However, modelling studies do not necessarily have to follow all the steps of this ideal protocol.

It was shown in Chapters 3, 5 & 6 that sap flow through the trunks of grapevines as well as evaporation from the soil surface could be estimated by means of certain parameters. A combination of the transpiration and evaporation models presented in these Chapters could serve as the basis for a water consumption model to estimate evapotranspiration by vineyards. Furthermore, using the appropriate parameters applicable to the conditions for a specific vineyard, estimation of water consumption for an individual vineyard or a group of vineyards, under comparable conditions, would be possible.

The purpose of this study was to construct and verify a model to estimate evapotranspiration in vineyards under South African conditions.

7.2 MATERIALS AND METHODS

The critical aspects of modelling protocol used to construct the water consumption model in this study included : 1) Defining the purpose of the model, 2) Selection and verification of equations for accurate description of the physical processes occurring in the vineyard, 3) Model design, *i.e.*

arrangement of the pertinent concepts in a suitable model, 4) Model verification to establish that the model can compute field measured values, and 5) A sensitivity analysis to establish the effect of uncertainty in certain inputs or parameters on model output. Other steps of the ideal modelling protocol as proposed by Anderson & Woessner (1992) were to some extent integrated in these five critical aspects. A further important aspect, which was not included in the ideal modelling protocol, is defining limitations to application of the model.

7.2.1 Defining the purpose of the model

A mathematical model is required to estimate water consumption of vineyard in such a way that it can account for variation among vineyards. The sources of this variation were identified and discussed in Chapter 1, the most important being grapevine canopy surface area as a function of trellis system, vigour and vine spacing as well as soil surface evaporation as a function of foliage cover, soil type, soil surface conditions and percentage wetted soil area. The latter is primarily a function of the irrigation system.

7.2.2 Selection and verification of governing equations

Selection and verification of equations for estimation of daily sap flow or transpiration, leaf area development and evaporation from the soil surface, which can be regarded as the processes governing the water consumption by the vineyard, are presented in detail in Chapters 3, 5 and 6, respectively. The equations employed will be presented in the following section on model design.

7.2.3 Model design

A schematic diagram to explain the design of the evaporation model is presented in Fig. 7.2. Details on the steps followed as well as the equations employed are as follows:

7.2.3.1 Sap flow model

Since it was shown in Chapter 3 that sap flow through grapevine trunks practically is equal to transpiration, water extracted by the grapevine for transpiration and maintaining cell turgidity will be referred to as sap flow or transpiration. The model proposed to estimate the variation in daily sap flow over the course of a growing season, is described by the following steps:

Step 1 : The seasonal variation in normalized leaf area index (LAI′) as a function of day of season (DOS) is calculated using the equations presented in Chapter 5. For the cooler Winter Rainfall Region the equation would be as follows :

$$LAI'_W = 0,00569\ DOS + 6,7\ E-05\ DOS^2 - 3,84\ E-07\ DOS^3 - 0,047 \qquad (7.1)$$

and for the warmer Summer Rainfall Region, *e.g.* the Lower Orange River Valley :

$$LAI'_S = 0{,}00666\ DOS + 2{,}3\ E - 05\ DOS^2 - 1{,}48\ E - 07\ DOS^3 - 0{,}027 \qquad (7.2)$$

Step 2 : Although estimating maximum leaf area from the linear relationship between leaf fresh mass and leaf area on a given day of season, *i.e.* equation 5.10 as proposed in Chapter 5, is more accurate, it is difficult to apply in practise. As an alternative, maximum leaf area per grapevine (LA_x) is estimated from cane mass by means of linear regression as discussed in Chapter 5. In the case of horizontal canopies the equation is :

$$LA_{xH} = 13{,}66\ M_P + 6{,}17 \qquad (7.3)$$

where LA_X is maximum leaf area per grapevine (m^2) and M_P is the cane mass (kg $vine^{-1}$). For vertical canopies the equation is as follows :

$$LA_{xV} = 7{,}81\ M_P - 0{,}23 \qquad (7.4)$$

Step 3 : Maximum leaf area index is obtained by dividing LA_X by the area (m^2) allocated to a grapevine (*i.e.* plant spacing) as follows:

$$LAI_x = LA_x\ /\ (W_P \times W_R) \qquad (7.5)$$

where W_P and W_R are distances (m) between grapevines in the row and between rows, respectively.

Step 4 : LAI on a specific day is calculated by means of the following equation :

$$LAI_n = LAI'_n \times LAI_x \qquad (7.6)$$

where n denotes a specific DOS.

Step 5 : Daily LAI_n is converted to actual leaf area (LA_n) in m^2 as follows :

$$LA_n = LAI_n\ (W_P \times W_R) \qquad (7.7)$$

Step 6 : Under conditions of no water stress, daily sap flow or transpiration per grapevine (Q) is calculated using leaf area per grapevine (LA_n) and either A-pan (E_p) or Penman-Monteith reference crop evapotranspiration (ET_o) as discussed in Chapter 3. In the case of horizontal canopies and using Class-A pan data, the equation to obtain Q (ℓ $d^{-1}vine^{-1}$) would be as follows :

$$Q_H = 0,338\ LA_n + 0,072\ ET_p - 0,443 \tag{7.8}$$

or when Penman-Monteith data are used as an alternative :

$$Q_H = 0,331\ LA_n + 0,185\ ET_o - 1,140 \tag{7.9}$$

When Class-A pan data are used, the equation for vertical canopies would be :

$$Q_V = 0,200\ LA_n + 0,043\ ET_p - 0,433 \tag{7.10}$$

or when Penman-Monteith data are used as an alternative :

$$Q_V = 0,199\ LA_n + 0,065\ ET_o - 0,401 \tag{7.11}$$

Step 7 : Total daily sap flow per hectare for horizontal canopies (Q_{TH}) is calculated and converted to mm as follows:

$$Q_{TH} = (Q_H \times N) / 10\,000 \tag{7.12}$$

For vertical canopies total daily sap flow (Q_{TV}) is calculated as follows :

$$Q_{TV} = (Q_V \times N) / 10\,000 \tag{7.13}$$

N is the number of grapevines per hectare and 10 000 is the area of one hectare (m^2).

7.2.3.2 Evaporation model

Evaporation from the soil surface (E_s) is estimated by means of the model proposed by Boesten & Stroosnijder (1986). Under the conditions of this study, foliage cover only reduced evaporation during stage one. Beta-values are adapted for specific soil types and canopy orientation as discussed in Chapter 6. The model design is as follows :

Step 1 : During stage one evaporation, E_s is estimated by summation of daily ET_o values until $\sum E_s$ equals β^2, a constant that has to be experimentally determined for specific soil types. To account for the effect of increases in foliage cover, $\sum ET_o$ during stage one is multiplied by the factors for specific trellis orientations on a monthly basis as presented in Chapter 6 (Table 6.4).

Step 2 : On the day when $\sum ET_o$ exceeds β^2, it is assumed that evaporation is in stage two. Hence, $\sum E_s$ is calculated as follows :

$$\sum E_s = \beta(\sum ET_o)^{0,5} \tag{7.14}$$

Step 3 : If required, E_s on a given day n is calculated as :

$$E_s(_n) = \sum E_{(s)\ (n)} - \sum E_{s\ (n-1)} \tag{7.15}$$

Step 4 : When irrigation or precipitation amounts exceeds $\sum E_{s(n)}$ and the soil water content is restored to field capacity, $\sum E_s$ is reset to zero and steps one and two are repeated (Boesten & Stroosnijder, 1986).

7.2.3.3 **Water consumption model**

The model calculates transpiration and evaporation from the soil separately on a daily basis as discussed above. These two parameters are then combined to obtain total daily ET. The inputs are as follows :

(i) Daily Class-A pan evaporation (E_p) or reference crop evapotranspiration (ET_o) as calculated by means of a modified Penman-Monteith equation.
(ii) Since the model distinguishes between canopy development in cool and warm areas, there is an option to select either equation 7.1 or 7.2.
(iii) Cane mass at pruning or fresh leaf mass per vine on a specific day of season (DOS) to calculate maximum leaf area index.
(iv) Canopy surface orientation, which can either be vertical or horizontal, to select either equation 7.8 or 7.10 if Class-A Pan data are used for the sap flow calculations. If Penman-Monteith data are used either equation 7.9 or 7.11 is selected.
(v) Plant spacing between grapevines and between rows, used in calculating leaf area, to convert volumetric sap flow to depth in mm and to calculate number of grapevines per hectare by means of equation 7.12 or 7.13.
(vi) A specific β-value, required to calculate evaporation losses from the soil surface by means of equations 7.14 and 7.15.
(vii) The amount of plant available water which is allowed to be extracted between irrigations.

The water consumption model can be operated in two ways. Long term average daily Class-A pan evaporation (E_p) or reference crop evapotranspiration (ET_o) can be used to calculate average daily evapotranspiration (ET) or crop coefficients on a monthly basis as well as total seasonal water requirements. Data obtained in this way can be used in planning water storage and supply systems or for irrigation system design. If actual daily E_p or ET_o values are used, real time daily evapotranspiration under no water stress conditions can be calculated. By using this option, the model can be used by growers for practical irrigation scheduling at farm level.

At this stage the model is only operated by means of a Microsoft DOS version of the Lotus 1-2-3 spreadsheet program. This facility is adequate, since testing and changes will be necessary before a final computer program can be developed for the practical application of the model. For the purpose of this study, only cumulative ET between rainfall events or irrigations were calculated by means of the model. Model output was as follows :

(i) A graphic display of cumulative ET (mm) between rain events or irrigations.
(ii) Total transpiration or sap flow (mm) from bud break until end of April.
(iii) Total surface evaporation (mm) from bud break until end of April.
(iv) Total ET (mm) from bud break until end of April.
(v) Maximum leaf area index.
(vi) Average crop coefficient (K_c or K_{cp}) for each month.
(vii) Average daily ET (mm) for each month.
(viii) Number of irrigations or rain events from bud break until end of April.

7.2.4 **Verification studies**

The accuracy and applicability of the draft water consumption model was verified by comparing predicted daily and cumulative ET against actual daily and cumulative ET of eight different vineyards as determined by means of field studies in previous research projects under a range of varying viticultural conditions. Determination of β-values for most of the soils used for the verification studies are presented in Chapter 6.

Verification study no. 1

In this case, water consumption of nine year old dryland Pinot noir grapevines planted in 1 200 mm deep soil was simulated by means of the model. Data were obtained from a field trial at the Nietvoorbij Centre for Vine and Wine near Stellenbosch where the effect of soil volume on grapevine response was studied. This locality is in a class III climatic region (Winkler, 1962) at 33° 55' latitude. The experimental layout, viticultural and soil management details were reported in full detail by Myburgh, Van Zyl & Conradie (1996). The soil was of the Glenrosa form (Soil Classification Work Group, 1991). Soil water content was determined weekly by means of the neutron scattering technique. Actual water consumption was calculated by means of the following universal water balance equation :

$$ET + SWC_b + I + P - SWC_e - D - R = 0 \qquad (7.16)$$

where ET is evapotranspiration over a given period, SWC_b and SWC_e are soil water content at the beginning and end of the period, respectively, I is irrigation applied, P is precipitation, D is drainage losses and R is runoff losses. All units were in millimetres. In this study, the irrigation term was not applicable, almost no runoff occurred and drainage losses were assumed to be zero. Daily Class-A pan evaporation, measured at a weather station approximately 1,5 km from the vineyard, was used to calculate reference crop evapotranspiration input data. Further inputs were a β-value of 2,1 $mm^{0,5}$ and the actual cane mass of 1,2 kg $vine^{-1}$. Predicted water consumption was compared to actual ET as measured from 5 September until 8 April during the 1993/94-season.

Verification study no. 2

In this example, water consumption of a sixteen year old Sultanina vineyard at the Department of Agriculture Northern Cape Experimental Station near Upington was simulated. This locality is in a class V climatic region (Winkler, 1962) at 28° 27' latitude. Data were obtained from a field trial where the effects of three flood irrigation methods and two irrigation cycle lengths on grapevine water consumption were investigated (Myburgh, unpublished data). Grapevines were trained onto a 2,4 m slanting trellis (Zeeman, 1981). Vine spacing was 3,0 m between rows and 1,5 m between grapevines. The alluvial soil was of the Dundee form (Soil Classification Work Group, 1991). The treatment used for the verification study was irrigated by means of full surface flood irrigation at 14 day intervals. Soil water depletion prior to irrigations was obtained by means of the neutron scattering technique. Irrigation water was extracted from a concrete canal system by means of a high volume, low pressure pump. Irrigation quantities were measured using a water meter mounted on the pump. Actual water consumption was calculated by means of equation 7.16. No runoff occurred and drainage losses were assumed to be zero. Daily Class-A pan evaporation, measured at the Upington Experimental Station, was used as reference crop evapotranspiration input parameter. A β-value of 3,71 $mm^{0,5}$ and the actual cane mass of 1,4 kg $vine^{-1}$ were used for this simulation. Simulated water consumption was compared to actual ET as determined from 2 September until 3 May during the 1993/94-season.

Verification study no. 3

In this study, water consumption of a twelve year old Sultanina vineyard on the SADOR farm of the South African Dried Fruit Co-operative near Upington was simulated. The climatic region and latitude are similar to that of Experiment no. 2. Data were obtained from a field trial where the effects of water stress during critical physiological stages on yield and quality of raisin grapes are investigated (Myburgh, unpublished data). Grapevines were trained onto a gable trellis system (Zeeman, 1981) and vine spacing was 3,0 m between rows and 2,0 m between grapevines. The red, sandy soil was of the Plooysburg form (Soil Classification Work Group, 1991). Grapevines were irrigated at a soil matrix potential of -30 kPa by means of 32 $\ell.h^{-1}$ micro-sprinklers. To maintain this depletion level, irrigations were generally applied weekly from bud break until November and then twice a week until February. During the post harvest period and winter, an irrigation was applied once a month. Changes in soil water matrix potential were measured by means of mercury manometer tensiometers. Soil matrix potential was converted to soil water content using soil water characteristic curves determined on undisturbed soil cores by means of the pressure membrane technique. Irrigation quantities were measured by means of water meters. Actual water consumption was calculated using equation 7.16. No runoff occurred and drainage losses were assumed to be zero. Actual daily reference crop evapotranspiration was calculated by means of a modified Penman-Monteith equation (Van Zyl, De Jager & Maree, 1989). Climatic parameters were measured hourly by means of an automatic weather station (MC-Systems) installed next to the vineyard. A β-value of 4,14 $mm^{0,5}$ and the actual cane mass of 2,4 kg $vine^{-1}$ were used in this simulation. Simulated water consumption was compared to actual ET as measured from 6 September until 30 April during the 1994/95-season.

Verification study no. 4

The water consumption of twelve year old drip irrigated Colombar/99 Richter grapevines at the ARC-Infruitec/Nietvoorbij Robertson Experimental Station in the Breede River Valley was also simulated. This locality is in a class V climatic region (Winkler, 1962) at 33° 50' latitude. Data were obtained from a field trial where the effect of plant available water (PAW) depletion levels and irrigation systems on grapevine response were studied. Experimental layout as well as viticultural, irrigation and soil management practices were reported in detail by Van Zyl (1984). The soil was classified as belonging to the Garies and Oakleaf forms (Soil Classification Work Group, 1991). Soil water matrix potential was measured by means of mercury manometer tensiometers and converted to soil water content by means of soil water characteristic curves. Irrigation amounts were calculated from the PAW deficit measured just prior to applications. Actual water consumption was calculated by means of equation 7.16. Runoff and drainage losses were assumed to be zero. Daily Class-A pan evaporation, as measured at the Robertson Experimental Station, was used as input parameter for reference crop evapotranspiration. A β-value of 3,2 $mm^{0,5}$ and the actual cane mass of 0,89 kg $vine^{-1}$ were used as inputs. Area wetted by drippers, *i.e.* where the highest evaporation losses would occur, was estimated to be 36 % of the total surface. This parameter was not assessed in the original study. To compare water consumption among vineyards used in the other verification studies, predicted and actual ET were calculated on the total area for this study. Simulated water consumption was compared to actual ET as determined from 2 September until 17 March during the 1982/83-season.

Verification study no. 5

A second simulation was done for grapevines in the same Colombar vineyard described in study no. 4. Soil water matrix potential was also measured by means of mercury manometer tensiometers and actual daily Class-A pan evaporation was used as input parameter for reference crop evapotranspiration. In this treatment grapevines were irrigated by means of 32 ℓ ha^{-1} micro-sprinklers at 10 % depletion of PAW (Van Zyl, 1984) A β-value of 3,2 $mm^{0,5}$ and actual cane mass of 1,07 kg $vine^{-1}$ were used as inputs. Simulated water consumption was compared to actual ET as measured from 2 September until 22 March during the 1982/83-season.

Verification study no. 6

Viticultural conditions as well as input parameters used in this simulation were similar to study no. 5, except that grapevines were irrigated at 50 % depletion of plant available water (Van Zyl, 1984). A β-value of 3,2 $mm^{0,5}$ and actual cane mass of 1,5 kg $vine^{-1}$ were used as inputs. Simulated ET was compared to actual ET as determined from 2 September until 16 March during the 1982/83-season.

Verification study no. 7

Water consumption of ten year old Bukettraube grapevines at the ARC-Infruitec/Nietvoorbij Lutzville Experimental Station in the Olifants River Valley was simulated in this study. This locality is in a class V climatic region (Winkler, 1962) at 31°36' latitude. Data were obtained from a fertigation field trial (Conradie & Myburgh, unpublished data). Grapevines were trained onto a slanting trellis (Zeeman, 1981). Due to the presence of a duripan, the fine, red, sandy soil was classified as belonging to the Garies form (Soil Classification Work Group, 1991). Vine spacing was 2,75 m between rows and 1,2 m between grapevines. Irrigations were applied twice a week by means of 32 ℓ h^{-1} micro-sprinklers. Soil water matrix potential was measured by means of mercury manometer tensiometers and converted to soil water content by means of soil water characteristic curves established *in situ*. Irrigation amounts were calculated from the PAW deficit just prior to applications. Actual water consumption was calculated by means of equation 7.16. No runoff occurred and drainage losses were assumed to be zero. Daily Class-A pan evaporation, as measured at the Lutzville Experimental Station, was used as input parameter for reference crop evapotranspiration. The actual cane mass was 0,4 kg $vine^{-1}$. Since the β-values for this soil was unknown, an appropriate value was selected by trial and error. Predicted ET was compared to actual ET as measured from 26 September until 22 March during the 1989/90-season.

Verification study no. 8

In this study, water consumption of Barlinka grapevines on a sandy soil in the Hex River Valley was simulated. Data were obtained from a field trial at the ARC-Infruitec/Nietvoorbij Hex Valley Experimental Station near De Doorns where the effects of PAW depletion on grapevine response were studied. This locality is in a class V climatic region (Winkler, 1962) at 33°28' latitude. Viticultural information and experimental details were presented by Myburgh (1996). Soil water depletion was measured weekly by means of mercury manometer tensiometers. Soil water matrix potential was converted to soil water content by means of soil water characteristic curves determined *in situ*. The specific treatment was irrigated at a soil water matrix potential of -5,0 kPa or 40 % depletion of PAW. Irrigation quantities were calculated by multiplying the application rate by the duration. Actual water consumption was calculated by means of equation 7.16. No runoff occurred and drainage losses were assumed to be zero. Daily Class-A pan evaporation measured at the Hex River Valley Experimental Station was used as input for reference crop evapotranspiration. A β-value of 4,68 $mm^{0,5}$ and actual cane mass of 1,8 kg $vine^{-1}$ were used as inputs. Predicted ET was compared to actual ET as determined from 4 September until 29 April during the 1993/94-season.

7.2.5 Sensitivity analysis

Sensitivity of the model to errors in input parameters was determined by calculating the percentage of actual values of daily and cumulative ET that were within the 95 % or 90 % confidence limits of the predicted values. For this purpose, standard errors of input parameters were calculated. Mean values of input parameter plus or minus the standard error were then used in the model to calculate the various confidence limits of the model. Standard errors of the input parameters were calculated as follows:

β-values : The sample variance of β-values as obtained in Chapter 6 was calculated by means of the following equation (Snedecor & Cochran, 1982):

$$V_\beta = 1/(n-1) \ [\sum\beta_i^2 - 1/n \ (\sum\beta)^2] \qquad 7.17$$

where V_β is the sample variance and n is the number of evaporation runs for which β were determined (Chapter 6 , Table 6.5). The standard deviation, s_β, was calculated as follows :

$$s_\beta = (V_\beta)^{0,5} \qquad 7.18$$

The standard error of each β-value ($mm^{0,5}$), se, was calculated using the following equation :

$$se = s_\beta \ (1/n)^{0.5} \qquad 7.19$$

Confidence limits for β-values were obtained from :

$$\beta \pm t \ se \qquad 7.20$$

where t is the Student's two-sided t-table value at a 95 % or 90 % probability and se is the standard error of the measured β-value (Snedecor & Cochran, 1982).

Cane mass : The confidence limits for cane mass (x) in the estimation of maximum leaf area (Chapter 5, equations 5.6 & 5.7) were calculated by means of the prediction of X from Y as follows (Snedecor & Cochran, 1982) :

$$x \pm 1/b(t \ se_{y,x}) \ (1 + 1/n + x^2/\sum x^2)^{0.5} \qquad 7.21$$

where b is the slope of the regression of maximum leaf area on cane mass (Equations 5.6 & 5.7), t is the probability of distribution, $se_{y,x}$ is the standard error of estimation of y, n is the number of observations and x is calculated using the mean of the leaf area data used to develop equations 5.8 & 5.9. $\sum x^2$ was calculated as follows :

$$\sum x^2 = \sum X_i^2 - 1/n \ (\sum X_i)^2 \qquad 7.22$$

were X denotes the cane mass values used to obtain the regression of leaf area on cane mass. The confidence limits were calculated for horizontal as well as vertical canopies.

7.2.6 Limitations to model application

Since the sap flow or transpiration models were derived from data obtained from irrigated vineyards where assumably no water stress occurred, these models will only by applicable under similar conditions. Hence, the models might not be applicable to vineyards on shallow sandy soils or under dryland conditions where water stress is likely to occur. Potential growth curves, which were established under no water stress conditions, will also limit model application. Furthermore, use of the potential growth curves will be limited to the localities where data were obtained from, *i.e.* the Winter Rainfall Region of the Western Cape and vineyards along the Lower Orange River in the Summer Rainfall Region. Validation of the model under water stress conditions and in other grape growing localities should be followed up during a post audit by comparing appropriate field data (Fig. 7.1).

7.3 RESULTS AND DISCUSSION

7.3.1 Draft water consumption model

An example where the Lotus 1-2-3 spreadsheet program was used to estimate water consumption and crop coefficients for a hypothetical wine grape vineyard in the Franschhoek area by means of a preliminary version of the model, is presented in Figure 7.3. A typical plant spacing of 2,75m between rows and 1,5 m between grapevines was chosen. Furthermore, it was assumed that the grapevines were trained onto a vertical trellis system and that a cane mass of 1 kg per vine was attained. The long term average daily Class-A pan evaporation, as measured at La Motte, was used as input for reference crop evapotranspiration. A β-value of 3,5 $mm^{0,5}$ was chosen and it was assumed that water holding capacity and root depth only allowed 50 mm soil water depletion between irrigations. It was also assumed that 100 % soil surface wetting was obtained during irrigation.

This example demonstrated how the model can be applied to estimate variation in mean daily water consumption or total seasonal water requirements for planning of water supplies or irrigation system design. If the model is used for these purposes, however, input parameters such as cane mass will have to be estimated. In general 2 kg per grapevine and 1 kg per grapevine can be used as a first approximation for well balanced, fully developed horizontal and vertical canopies, respectively. However, such guidelines should be improved by further research to increase the accuracy of the water consumption model. If long term average daily E_p or ET_o values are used to compile seasonal irrigation schedules for existing vineyards, it would be possible to measure input parameters such as cane mass or leaf fresh mass on a specific DOS.

Due to the unreliability and uneven distribution of rainfall in most South African grape growing regions, it would be a more realistic and safer approach not to depend on rainfall as a given input to the soil water balance. Hence, when using the model to estimate water consumption for planning and design, the contribution of possible rainfall is ignored.

7.3.2 Verification of the water consumption model

Verification study no. 1

In general the simulated mean daily ET and crop coefficients corresponded reasonably well with the actual data (Table 7.1). This was confirmed by the fact that the value of one, which indicates a 1 : 1 relationship, was within the 5 % confidence limits calculated for the slope of the regression of predicted ET on actual ET (Table 7.9). The lower predicted daily ET during January was probably the result of experimental error. Predicted cumulative seasonal ET also satisfactorily followed the course of actual cumulative ET measured in the field (Fig. 7.4A). Actual total seasonal evapotranspiration was underestimated by 6,0 % (Table 7.11).

Verification study no. 2

Predicted and actual mean daily ET agreed reasonably well until January (Table 7.2). From February until April the model overestimated daily ET. The reason for the overestimation could be as follows: The Plant Canopy Analyzer used in developing the model to estimate seasonal leaf area variation as discussed in Chapter 4, could not distinguish between physiologically active and dead leaves still remaining on grapevines. Hence, the water consumption model assumes that all leaves remaining on grapevines during the post harvest period, will transpire normally. However, it could be that transpiration rates decrease due to ageing of the leaves or some degree of abscission in petioles. This possible reduction in transpiration could be responsible for the lower actual water consumption in comparison to the values predicted by means of the model. Confirmation and assessment of this effect is part of an ongoing study. Despite the overestimation, the value of one was still within the 5 % confidence limits of the regression of predicted data on actual data (Table 7.9). Simulated seasonal cumulative ET pattern was almost identical to the course of actual cumulative ET (Fig. 7.4B). The model only overestimated total seasonal evapotranspiration by 3,2 % (Table 7.11).

Verification study no. 3

Predicted daily ET tended to be lower in comparison to the actual field data (Table 7.3). Under the experimental conditions drainage losses, which could not be accounted for, probably occurred frequently. Since possible drainage losses were regarded as part of ET in the water balance equation, it could be the reason for the higher actual values. Due to the underestimation, the value of one was outside the 5 % confidence limits calculated for the slope of the regression of predicted ET on actual ET (Table 7.9). The deviation during April could be for the same reason as discussed for study no. 2, namely overestimation of transpiration during the post harvest period. The fact that the grapevines were well watered until March could have postponed ageing of leaves and abscission which resulted in higher mean daily transpiration rates in comparison to the situation in verification study no. 2 where post harvest irrigations were applied at six week intervals. Higher evaporation losses, resulting from shorter irrigation cycles, could also have contributed to the higher mean daily transpiration rates, in comparison to the 14 day intervals in study no. 2 (Table 7.10).

Simulated seasonal cumulative ET deviated somewhat from the actual cumulative ET pattern during the middle and late season (Fig. 7.4C). The model underestimated actual seasonal cumulative evapotranspiration by 1,8 % (Table 7.11).

Verification study no. 4

Predicted ET correlated reasonably well with actual ET (Table 7.4). This was confirmed by the fact that the value of one was within the 5 % confidence limits calculated for the slope of the regression of predicted ET on actual ET (Table 7.9). The reasonably good agreement between predicted and actual mean daily ET indicated that the model is suitable for estimation of ET in the case of drip irrigation or strip wetting where evaporation from the soil surface primarily occurs on the wetted area. Simulated cumulative ET closely followed the course of actual cumulative ET over the season (Fig. 7.4D). Actual total ET was overestimated by 4,7 % (Table 7.11).

Verification study no. 5

Predicted ET correlated reasonably well with actual ET (Table 7.5). This was confirmed by the fact that the value of one was within the 5 % confidence limits calculated for the slope of the regression of predicted data on actual data (Table 7.9). In this study, however, the model did not over-estimate ET during the last part of the season. Since Colombar is a late cultivar, which only ripens during March in this particular region, transpiration probably remained unaffected by ageing during the period under consideration. The fairly high soil water content level could also have delayed leaf ageing and abscission in comparison to the grapevines in study no. 2. Simulated cumulative ET followed the course of actual cumulative ET fairly satisfactorily over the season (Fig 7.5A). Actual total ET was underestimated by 0,6 % (Table 7.11).

Verification study no. 6

Simulated mean daily ET also correlated reasonably well with actual mean daily ET (Table 7.6). The value of one was within the 5 % confidence limits calculated for the slope of the regression of predicted ET on actual ET (Table 7.9). This suggested that the model would be sensitive enough to simulate effects of different soil water depletion levels during various physiological stages. Simulated seasonal cumulative ET also followed actual field values closely (Fig. 7.5B). The model overestimated actual seasonal ET by only 0,5 % (Table 7.9).

In general, predicted daily ET was higher in comparison to actual values (Table 7.6). This could be due to the fact that the model did not account for reduced transpiration when limited water stress occurred. In the case of 10 % PAW depletion, differences between predicted and actual values were notably less.

Seasonal ET was appreciably lower for 50 % depletion of available soil water in comparison to 10 % depletion of PAW (Fig. 7.5A). Estimated total transpiration of grapevines irrigated at 10 % PAW depletion was 21,5 % lower compared to 50 % PAW depletion (Table 7.10). Estimated maximum leaf area index of the 10 % PAW depletion treatment, however, was 24,4 % lower in comparison to 50 % PAW depletion. This suggested that, although grapevines irrigated at 10 % PAW depletion experienced less water stress (Van Zyl, 1984), total seasonal transpiration was dominated by total leaf area. Hence, total transpiration would probably have been higher in the case of 10 % PAW depletion if leaf areas were comparable. On the other hand, higher evaporation losses due to more frequent wetting, caused total evapotranspiration of the 10 % PAW depletion treatment to be 27,9 % higher compared to the 50% PAW depletion treatment.

Verification study no. 7

Predicted ET agreed reasonably well with actual ET when a β-value of 2,2 $mm^{0,5}$ was used (Table 7.7). The value of one was within the 5 % confidence limits calculated for the slope of the regression of predicted ET on actual ET(Table 7.9). In this case, transpiration of the relatively limited canopy was notably less than evaporation losses from the soil surface (Table 7.10). The short irrigation cycles also contributed to the relatively high evaporation losses, despite the low β-value. Simulated cumulative ET corresponded closely to the actual cumulative ET over the season (Fig. 7.5C). Actual total seasonal ET was overestimated by 0,9 % (Table 7.11).

Verification study no. 8

Simulated mean daily ET correlated reasonably well with actual mean daily ET (Table 7.8). The value of one was within the 5 % confidence limits calculated for the regression of predicted ET on actual ET (Table 7.9). The high actual daily ET values were the result of the high evaporation losses (Table 7.9). This is in agreement with the β-value of 4,68 $mm^{0,5}$, which was the highest for the six soil types used in the evaporation study presented in Chapter 6. The high crop coefficients (Table 7.8) agreed with crop coefficients of 0,91 and 0,79 for Barlinka irrigated at -5,0 kPa on a similar soil type in the Hex River Valley, as determined in previous research (Fourie, 1989). Simulated seasonal cumulative ET also followed the course of actual cumulative ET closely (Fig. 7.5D). Actual total seasonal ET was overestimated by 3,8 %.

7.3.3 **Sensitivity analysis**

Confidence limits for the prediction of daily evapotranspiration if 5 % or 10 % error in β-value and cane mass were allowed, are presented in Tables 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7 & 7.8. In six of the eight verification studies, 100 % of the actual daily ET values were within the confidence limits if 5 % error were allowed in β-values or cane mass. In verification studies no's. 3 and 8 62,5 % and 75 % of the actual values were within the confidence limits, respectively. The reason for all actual values not being within limits were not caused by error in the input parameters, but by experimental errors as discussed earlier. The same arguments would be valid if 10 % error is allowed in the input parameters. Furthermore, it must be noted that the confidence limits were a combination of errors in β-value and cane mass. In general, it can be assumed that if 5 % to

10 % errors in β-value and cane mass occur, the accuracy of predicted daily ET will still be within acceptable confidence limits. Confidence limits for the prediction of seasonal cumulative evaporation if 5 % or 10 % error in β-value and cane mass were allowed, are presented in Table 7.11. For the eight verification studies actual cumulative ET values were within the 5 % as well as 10 % confidence limits. These results showed that if 10 % error is allowed, the accuracy of predicted cumulative ET will be within acceptable confidence limits.

7.4 CONCLUSIONS

Verification studies, where simulated ET was compared to actual ET, measured for eight vineyard situations, showed that the crop-specific model can predict ET satisfactorily. These vineyards represented a set of variables which ranged from dryland to flood and drip irrigation. Soil type, soil water depletion level, canopy orientation and vigour were also accounted for. Furthermore, it was shown that only simple inputs are required. Viticultural inputs such as cane mass, plant spacing and canopy surface orientation can easily be obtained by growers. Reference crop evapotranspiration data for the nearest weather station can be obtained from a national meteorological data base, *e.g.* the service provided by the ARC-Institute for Soil Climate and Water in Pretoria. Beta-values required for the estimation of evaporation losses for specific soil types should be provided by research institutions such as ARC-Infruitec/Nietvoorbij.

One of the major shortcomings of the model is the uncertainty about the relation between leaf area and transpiration during the post harvest period. The effect of limited soil water deficits on transpiration should also be investigated. These problems should be addressed by further research. The inadequate list of known β-values will limit the application of the model. Hence, it is vital to determine this parameter for more soil types. Furthermore, research in this regard should be aimed at establishing means to predict the variation in β-values for soils as well as different tillage practices applied in South African vineyards.

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TABLE 7.1

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for dryland Pinot noir grapevines on a vertical canopy at Stellenbosch during the 1995/96-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,21	0,26	0,96	1,07	*0,87*	*1,30*	*0,91*	*1,25*
October	0,44	0,42	2,08	2,19	*1,78*	*2,57*	*1,86*	*2,50*
November	0,30	0,27	2,20	1,93	*1,53*	*2,32*	*1,61*	*2,24*
December	0,35	0,36	2,07	2,08	*1,63*	*2,49*	*1,72*	*2,43*
January	0,17	0,15	1,55	1,63	*1,24*	*2,01*	*1,32*	*1,94*
February	0,31	0,31	1,96	1,98	*1,54*	*2,42*	*1,62*	*2,34*
March	0,19	0,19	0,99	1,01	*0,76*	*1,26*	*0,81*	*1,21*
April	0,16	0,20	0,65	0,72	*0,53*	*0,91*	*0,57*	*0,88*

TABLE 7.2

Comparison between actual predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for flood irrigated Sultanina grapevines on a horizontal canopy at Upington during the 1993/94-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,46	0,46	2,56	2,59	*2,34*	*2,79*	*2,38*	*2,75*
October	0,48	0,48	4,48	4,31	*3,84*	*4,79*	*3,93*	*4,70*
November	0,47	0,46	4,40	4,16	*3,59*	*4,74*	*3,69*	*4,63*
December	0,47	0,50	5,28	5,32	*4,57*	*6,07*	*4,70*	*5,93*
January	0,49	0,52	4,03	4,00	*3,27*	*4,73*	*3,40*	*4,60*
February	0,53	0,66	3,60	4,22	*3,41*	*5,04*	*3,56*	*4,89*
March	0,43	0,58	2,22	2,64	*1,99*	*3,29*	*2,10*	*3,18*
April	0,34	0,54	1,48	2,06	*1,48*	*2,63*	*1,58*	*2,53*

TABLE 7.3

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for micro-sprinkler irrigated Sultanina grapevines on a horizontal canopy at Upington during the 1994/95-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,50	0,46	2,13	2,08	*2,05*	*2,30*	*2,02*	*2,28*
October	0,44	0,44	2,68	2,70	*2,42*	*2,98*	*2,47*	*2,92*
November	0,72	0,65	5,66	5,09	*4,54*	*5,61*	*4,64*	*5,51*
December	0,67	0,65	6,04	5,80	*5,02*	*6,44*	*5,15*	*6,33*
January	0,64	0,60	5,40	5,10	*4,43*	*5,78*	*4,55*	*5,66*
February	0,71	0,67	5,19	4,91	*4,24*	*5,58*	*4,37*	*5,46*
March	0,73	0,67	3,54	3,03	*2,69*	*3,37*	*2,75*	*3,30*
April	0,39	0,56	1,90	2,57	*2,24*	*2,76*	*2,29*	*2,72*

TABLE 7.4

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for drip irrigated Colombar grapevines on a horizontal canopy at Robertson during the 1982/83-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,23	0,22	0,83	0,74	*0,61*	*0,87*	*0,64*	*0,84*
October	0,25	0,28	1,41	1,54	*1,20*	*1,87*	*1,26*	*1,81*
November	0,34	0,32	2,34	2,33	*1,79*	*2,88*	*1,89*	*2,78*
December	0,38	0,37	3,24	3,15	*2,38*	*3,87*	*2,52*	*3,74*
January	0,39	0,40	3,42	3,47	*2,55*	*4,39*	*2,71*	*4,23*
February	0,46	0,47	3,15	3,25	*2,36*	*4,02*	*2,52*	*3,93*
March	0,25	0,29	1,60	1,86	*1,21*	*2,52*	*1,33*	*2,40*

TABLE 7.5

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for micro-sprinkler irrigated Colombar grapevines on a horizontal canopy at Robertson during the 1982/83-season. (Irrigations were applied at 10 % PAW depletion).

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
					95 %		*90 %*	
	Actual	Predicted	Actual	Predicted	*lower limit*	*upper limit*	*lower limit*	*upper limit*
September	0,39	0,38	1,51	1,49	*1,26*	*1,72*	*1,31*	*1,67*
October	0,62	0,62	3,32	3,39	*2,83*	*3,94*	*2,95*	*3,84*
November	0,53	0,53	3,71	3,76	*3,00*	*4,52*	*3,14*	*4,38*
December	0,65	0,65	5,48	5,23	*4,16*	*6,29*	*4,36*	*6,09*
January	0,67	0,67	5,87	5,97	*4,73*	*7,22*	*4,96*	*6,99*
February	0,63	0,63	4,61	4,68	*3,61*	*5,75*	*3,81*	*5,55*
March	0,76	0,76	4,45	4,54	*3,55*	*5,52*	*3,73*	*5,34*

TABLE 7.6

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for micro-sprinkler irrigated Colombar grapevines on a horizontal canopy at Robertson during the 1981/82-season. (Irrigations were applied at 50 % PAW depletion).

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,29	0,27	0,85	0,89	*0,77*	*1,08*	*0,79*	*1,04*
October	0,17	0,21	0,95	1,14	*0,90*	*1,39*	*0,94*	*1,35*
November	0,50	0,55	3,07	3,49	*2,82*	*4,16*	*2,95*	*4,03*
December	0,59	0,60	4,98	5,04	*4,06*	*6,02*	*4,24*	*5,84*
January	0,56	0,58	4,85	4,98	*3,95*	*6,02*	*4,14*	*5,83*
February	0,63	0,61	4,39	4,08	*3,16*	*4,99*	*3,33*	*4,83*
March	0,45	0,58	2,79	3,63	*2,81*	*4,45*	*2,96*	*4,30*

TABLE 7.7

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for micro-sprinkler irrigated Bukettraube grapevines on a horizontal canopy at Lutzville during the 1989/90-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
October	0,57	0,50	4,22	3,72	*3,10*	*4,35*	*3,14*	*4,31*
November	0,47	0,48	4,14	4,14	*3,30*	*4,98*	*3,35*	*4,94*
December	0,45	0,45	4,40	4,49	*3,48*	*5,50*	*3,53*	*5,45*
January	0,51	0,50	4,93	4,87	*3,76*	*5,99*	*3,81*	*5,95*
February	0,47	0,49	4,19	4,35	*3,31*	*5,39*	*3,36*	*5,34*
March	0,36	0,37	2,75	2,79	*2,06*	*3,52*	*2,09*	*3,49*

TABLE 7.8

Comparison between actual and predicted mean monthly Class-A pan crop evaporation coefficients and daily evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for estimation of ET as determined by the simulation of ET for micro-sprinkler irrigated Barlinka grapevines on a horizontal canopy at De Doorns during the 1993/94-season.

Month	Crop coefficient		ET (mm d^{-1})		*Confidence limits for ET (mm d^{-1})*			
	Actual	Predicted	Actual	Predicted	*95 %*		*90 %*	
					lower limit	*upper limit*	*lower limit*	*upper limit*
September	0,60	0,59	3,16	2,85	*2,66*	*3,04*	*2,69*	*3,01*
October	0,49	0,56	3,43	3,88	*3,53*	*4,24*	*3,59*	*4,18*
November	0,55	0,59	4,33	4,65	*4,14*	*5,16*	*4,23*	*5,07*
December	0,58	0,50	4,92	4,29	*3,70*	*4,88*	*3,80*	*4,78*
January	0,70	0,73	6,03	6,31	*5,52*	*7,10*	*5,66*	*6,97*
February	0,70	0,72	4,96	5,11	*4,37*	*5,84*	*4,50*	*5,72*
March	0,88	0,83	5,04	4,86	*4,20*	*5,52*	*4,31*	*5,4*
April	0,95	0,98	3,79	3,91	*3,45*	*4,37*	*3,53*	*4,29*

TABLE 7.9

Regression data for relationship between estimated and actual ET as determined during verification of the water consumption model.

Verification study no.	Viticultural particulars and locality	Slope	R^2	Standard error of slope
1	Pinot noir, dryland, Stellenbosch	0,9988	0,9492	± 0,0271
2	Sultanina, flood irrigated, Upington	1,0203	0,8922	± 0,0348
3	Sultanina, micro-sprinkler irrigated, Upington	0,9458	0,9448	± 0,0276
4	Colombar, drip irrigated, Robertson	1,0158	0,9831	± 0,0202
5	Colombar, micro-sprinkler irrigated, Robertson*	1,0023	0,9926	± 0,0109
6	Colombar, micro-sprinkler irrigated, Robertson**	1,0043	0,9834	± 0,0234
7	Bukettraube, micro-sprinkler irrigated, Lutzville	0,9885	0,8957	± 0,0232
8	Barlinka, micro-sprinkler irrigated, De Doorns	1,0051	0,8699	± 0,0286

* Irrigated at 10 % plant available water depletion.
** Irrigated at 50 % plant available water depletion.

TABLE 7.10

Estimated maximum leaf area index, total seasonal transpiration, evaporation and evapotranspiration for eight vineyard situations as determined during verification of the water consumption model.

Verification study no.	Viticultural particulars and locality	Maximum leaf area index ($m^2\ m^{-2}$)	Transpiration* (mm)	Evaporation* (mm)	Evapotranspiration* (mm)
1	Pinot noir, dryland, Stellenbosch	2,40	57	256	313
2	Sultanina, flood irrigated, Upington	5,60	314	591	905
3	Sultanina, micro-sprinkler irrigated, Upington	6,74	318	645	963
4	Colombar, drip irrigated, Robertson*	3,88	163	283	446
5	Colombar, micro-sprinkler irrigated, Robertson**	4,49	194	596	789
6	Colombar, micro-sprinkler irrigated, Robertson***	5,94	247	370	617
7	Bukettraube, micro-sprinkler irrigated, Lutzville	2,91	137	540	677
8	Barlinka, micro-sprinkler irrigated, De Doorns	5,80	276	748	1024

* Based on total area irrespective of wetted soil volume.
** Irrigated at 10 % plant available water depletion.
***Irrigated at 50 % plant available water depletion.

TABLE 7.11

Comparison between actual and predicted seasonal cumulative evapotranspiration (ET), as well as the 95 % and 90 % confidence limits for prediction of cumulative ET as determined during verification of the water consumption model.

Verification study no.	Cumulative ET (mm)		*Confidence limits for Cumulative ET (mm)*			
	Actual	Predicted	*95 %*		*90 %*	
			lower limit	*upper limit*	*lower limit*	*upper limit*
1	333	313	*278*	*427*	*294*	*413*
2	877	905	*760*	*1051*	*786*	*1024*
3	971	963	*812*	*1025*	*831*	*1006*
4	426	446	*328*	*560*	*351*	*539*
5	794	789	*627*	*952*	*657*	*922*
6	614	617	*521*	*789*	*546*	*763*
7	671	677	*558*	*869*	*566*	*861*
8	986	1024	*902*	*1147*	*923*	*1126*

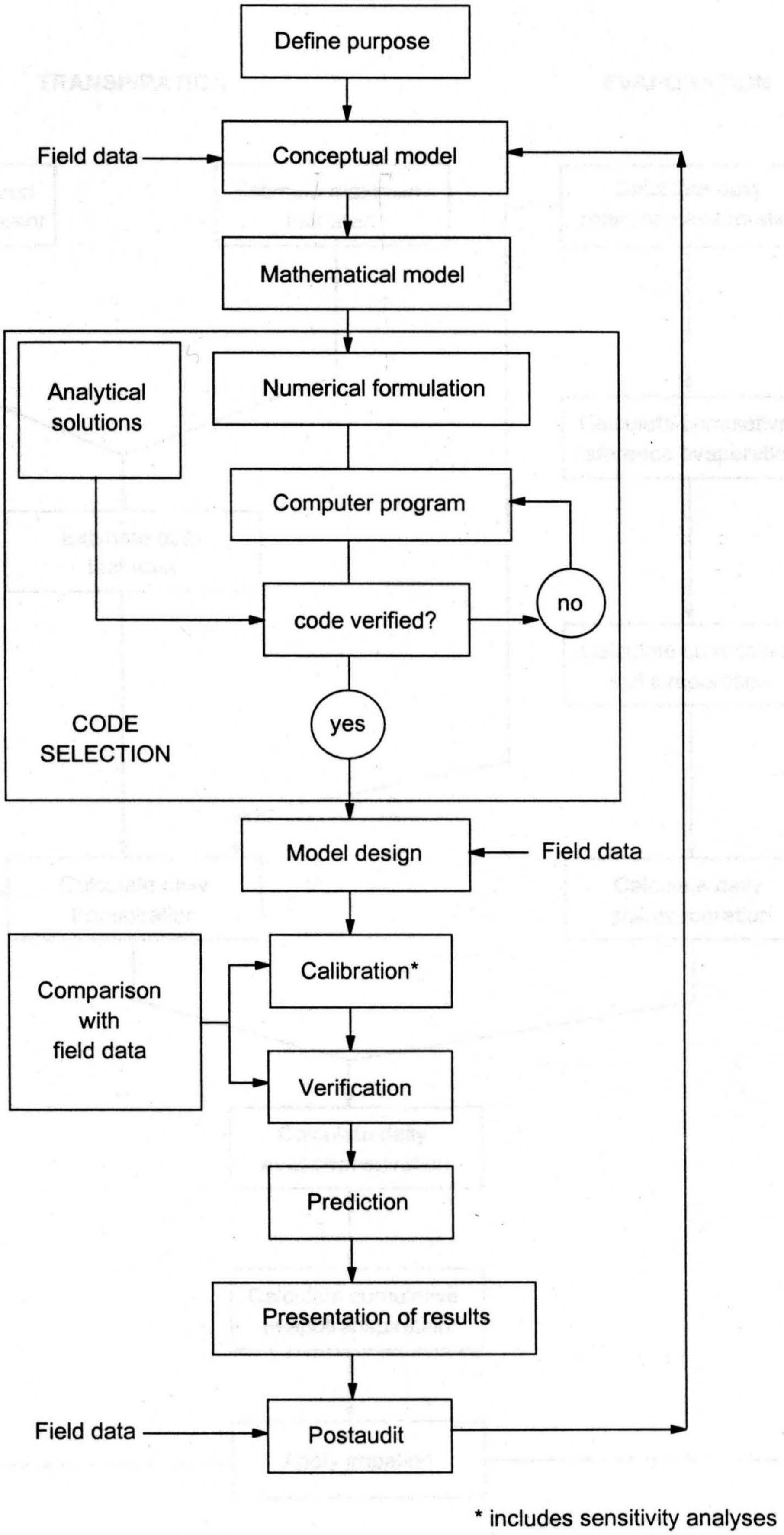


Figure 7.1. Steps in a protocol for model application (Anderson & Woessner, 1992).

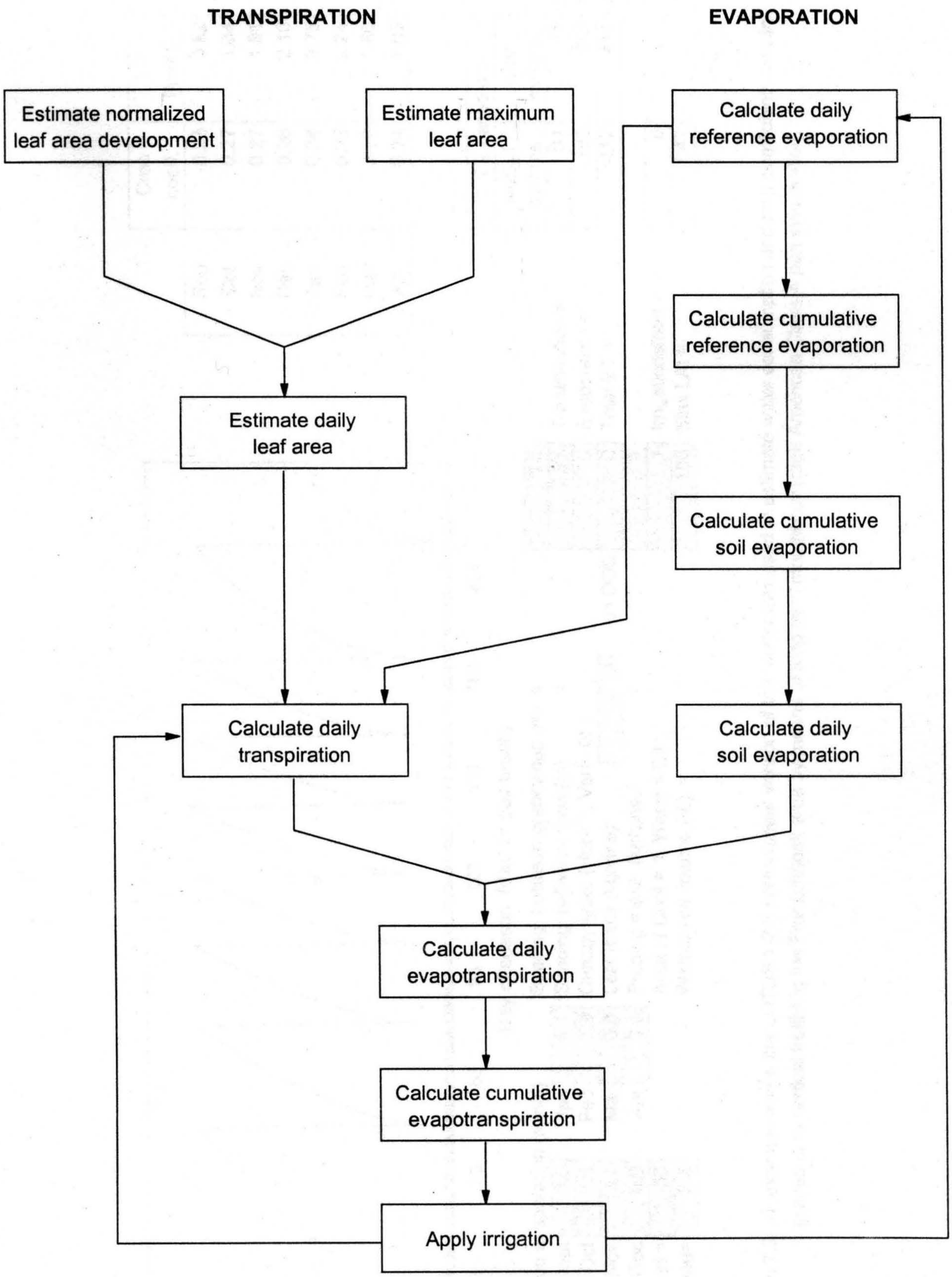
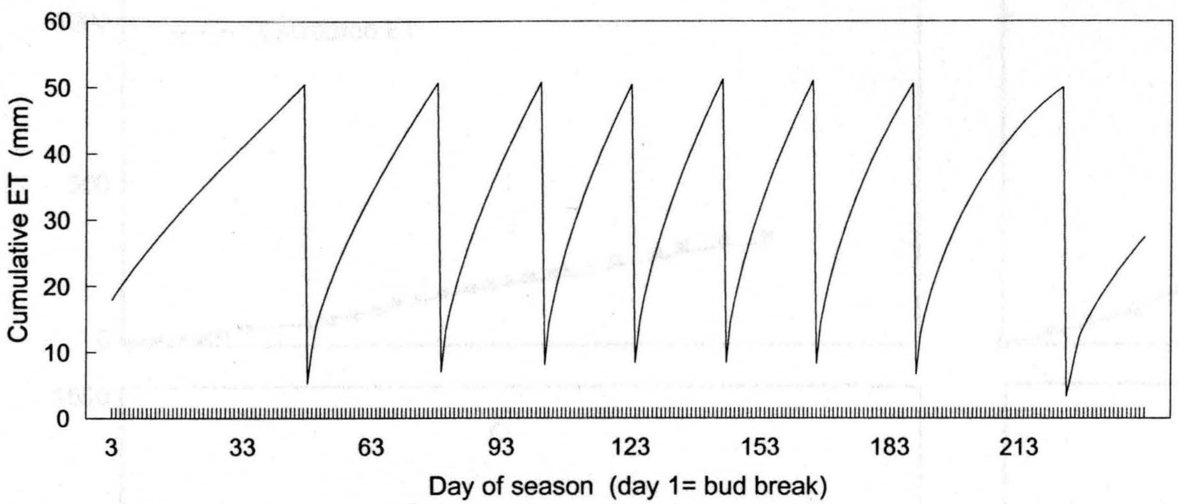


Figure 7.2. Design of draft model for calculating grapevine water consumption between irrigations.



	Crop coeff.	ET (mm/d)
Sep	0.23	0.82
Oct	0.27	1.34
Nov	0.27	1.81
Dec	0.26	2.10
Jan	0.34	2.75
Feb	0.28	2.24
Mar	0.29	1.66
Apr	0.34	1.03

Reference evaporation (mm/d)

Sept	3.6	Jan	8.1
Oct	5.0	Feb	7.9
Nov	6.7	Mar	5.8
Dec	8.0	Apr	3.0
SW depl.=	50		
Slope=	3.5		

Spacing between grapevines (m) =	1.5
Spacing between rows (m) =	2.75
Canopy type: (Hor= 1, Vert= 0) :	0
Leaf mass (kg/vine): 0 on DOS	0
Pruning mass (kg/vine) =	1
Area : (Cool = 1, Warm = 0) :	1
Wetted soil volume (%) =	100

	ET based on wetted surface	ET based on total surface	
Transpiration =	34	34	mm
Evaporation =	383	383	mm
Total ET =	417	417	mm

Irrigations/rain =	8
Max LAI =	1.47

Figure 7.3. An example where the LOTUS 1-2-3 spreadsheet version of the model was used to estimate water consumption and crop coefficients for wine grapes on a vertical trelllis in the Franschhoek area by means of long term monthly average American Class-A pan evaporation.

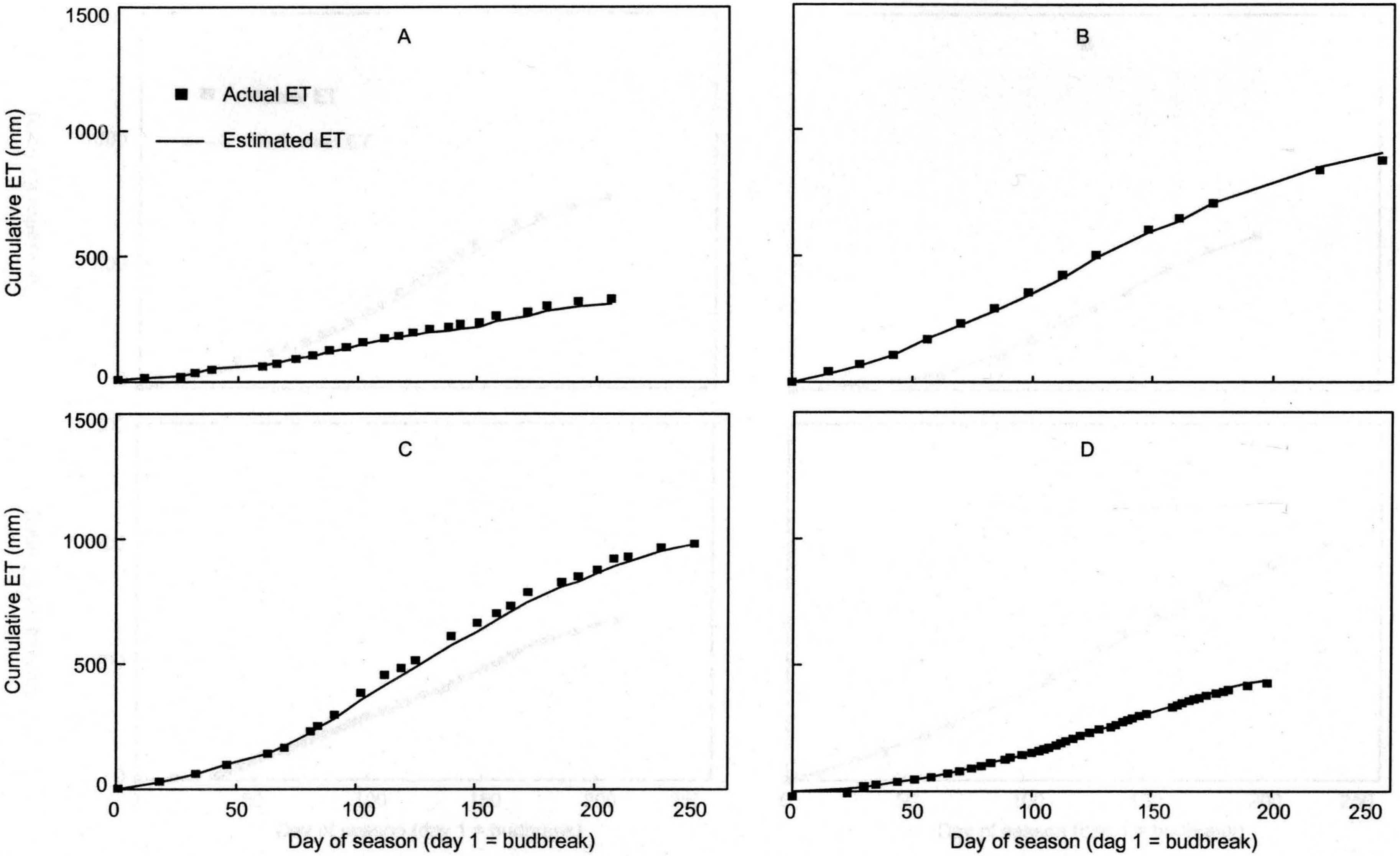


Figure 7.4. Predicted versus actual ET as determined for (A) dryland Pinot noir on sandy clay loam soil at Stellenbosch, (B) flood irrigated Sultanina on sandy loam soil at Upington, (C) micro-sprinkler irrigated Sultanina on sandy soil at Upington and (D) drip irrigated Colombar on sandy loam at Robertson.

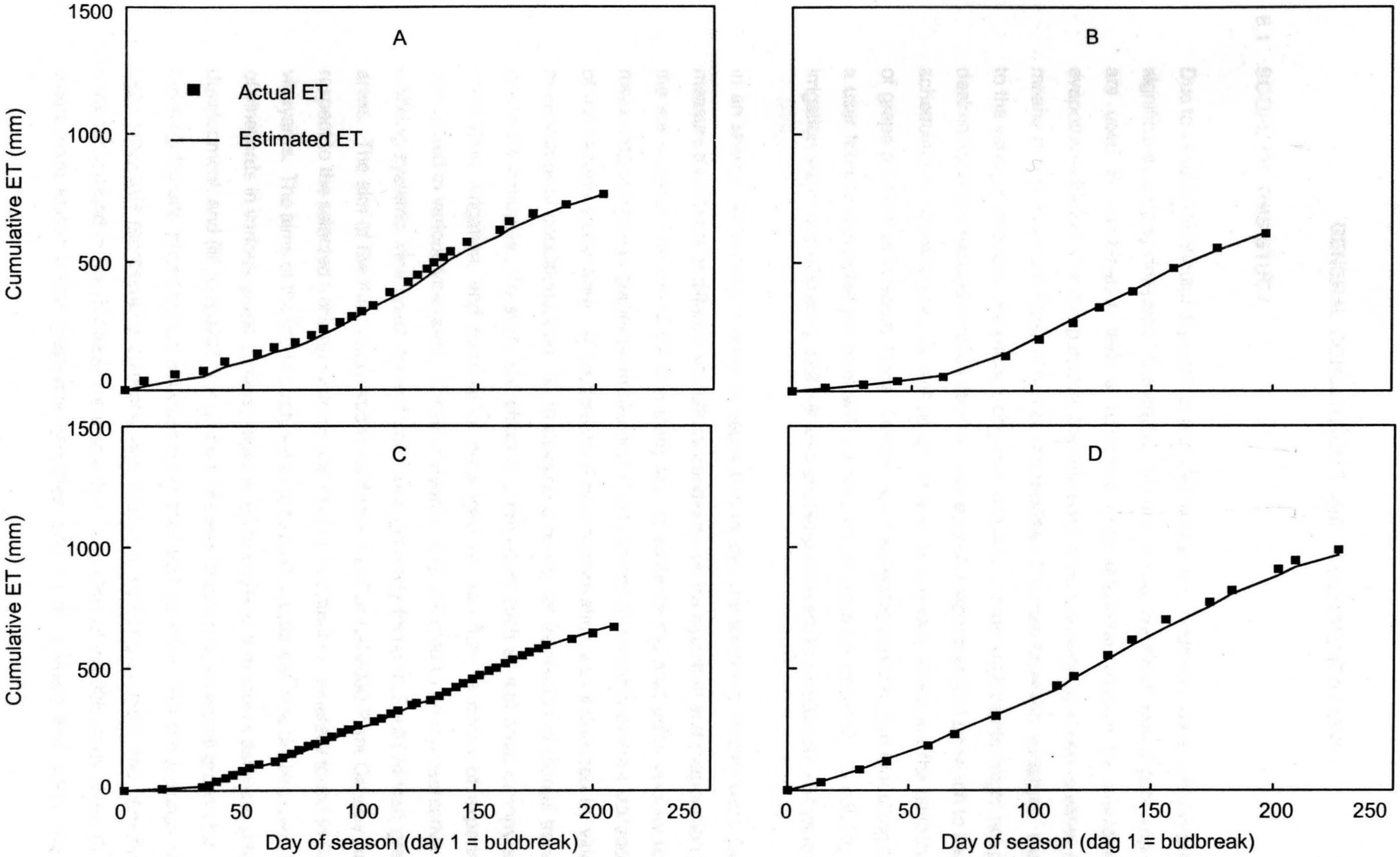


Figure 7.5. Predicted versus actual ET as determined for (A) Colombar on sandy loam soil at Robertson irrigated at 10% depletion of plant available water, (B) Colombar on the same soil irrigated at 50% depletion of plant available water, (C) Bukettraube on sandy soil at Lutzville and (D) Barlinka on sandy soil at De Doorns. All vineyards were irrigated by means of micro-sprinklers.

CHAPTER 8

GENERAL CONSLUSIONS AND RECOMMENDATIONS

8.1 SCOPE OF THIS STUDY

Due to variation in viticultural practices and meteorological conditions, water consumption can vary significantly among vineyards. Generally, only one or two "standard" sets of pan crop coefficients are used in combination with a reference crop evapotranspiration to estimate or model evapotranspiration. For this purpose, the reference crop evapotranspiration is either obtained by means of the American Class-A pan or the modified Penman-Monteith equation. However, due to the variation between vineyards, using only two sets of crop coefficients, might not produce the desired accuracy needed for estimation of crop evapotranspiration (ET) on which to base irrigation scheduling to optimize yield as well as grape and wine quality which are the ultimate objectives of grape production in South Africa. Hence, accurate water consumption modelling by means of a user friendly computer program will not only be of value for irrigation scheduling to improve irrigation water use efficiency, but will also enable producers to manipulate soil water content.

In an attempt to develop a water consumption model, the following studies were carried out to measure the effects of different viticultural conditions on transpiration and evaporation losses from the soil surface: The aim of the first study was to calibrate the heat pulse velocity technique for measuring sap flow in grapevine trunks over short periods of time after probe installation. The aims of the second study were: (i) to determine how transpiration was influenced by viticultural and meteorological conditions, and (ii) to develop a model for estimation of diurnal transpiration by grapevine canopies. To study the effect of parameters such as leaf area, canopy surface area orientation, irrigation, and removal of crop load on sap flow, a series of experiments were conducted in various vineyards. These vineyards were selected to be representative of cultivars, trellising systems, vine spacings and soil types generally found in South African grape growing areas. The aim of the third study was to calibrate a Li-Cor LAI-2000 Plant Canopy Analyzer with respect to the selected trellising systems and canopy orientations generally found in South African vineyards. The aims of the fourth study were: (i) to assess total leaf area development in a number of vineyards in various grape growing regions, (ii) to develop a model to estimate actual leaf area development, and (iii) to quantify the amount of water required by seasonal growth for maintaining cell turgidity and physiological activities other than transpiration. For the purpose of this study, eight vineyards representing cultivars, vine spacings, trellising systems and climatic conditions commonly found in South Africa, were selected. The aims of the fifth study were: (i) to measure evaporation losses under grapevine canopies, and (ii) to evaluate and adapt the Boesten &

Stroosnijder model for estimation of evaporation from vineyard soils.

The purpose of the sixth study was to construct and verify a model to estimate evapotranspiration of vineyards under South African conditions. The critical aspects of modelling protocol used to construct the model included : 1) Defining the purpose of the model, 2) Selection of governing equations and verification of equations to ensure accurate description of physical processes occurring in the vineyard, 3) Model design to put the draft model in a form suitable for modelling, 4) Model verification to establish that the model can reproduce field measured values, and 5) A sensitivity analysis to establish the effect of uncertainty in the model.

8.2 GENERAL CONCLUSIONS

- The heat pulse velocity technique could be employed to successfully estimate sap flow in grapevine trunks. A curvilinear calibration curve of sap flux against time can be applied to estimate sap flow in grapevines.

- Since wound effects, which may influence sap flow rates in long term experiments were ignored, these empirical calibrations would only be applicable where sap flow rates in grapevine trunks are measured within a week after probe installation.

- The similarity of the calibration curve obtained for excavated grapevines to the curve obtained for the undisturbed potted vine showed that, although water uptake rates of the excavated grapevines were lower, the actual process of water translocation in trunks were not disrupted.

- At least four probes should be used per grapevine trunk to account for sap flow variability induced by non-homogeneous xylem vessels.

- Estimating sap flow by means of the heat pulse velocity technique revealed that the amount of diurnal sap flow increased with leaf area.

- Hourly sap flow did not increase linearly with net radiation which suggested that maximum stomatal opening only allowed a fixed amount of transpiration.

- Sap flow showed a temporary decrease during the day, irrespective of increasing net radiation which indicated towards a possible water saving mechanism resulting from stomatal closure at high light intensities during mid-day.

- Eighty percent of variation in total diurnal sap flow could be explained by means of linear regression when only leaf area and reference crop evapotranspiration (ET_o) or Class-A pan evaporation (E_p) were considered. However, due to differences in the amount of leaves exposed to direct net radiation, variation in sap flow was predicted more accurately by individual linear models for horizontal and vertical canopies, respectively.

- The close relationship between leaf are per grapevine and sap flow indicated that sap flow was practically equal to transpiration.

- The Li-Cor PCA underestimated actual leaf area index. Decreasing the field of view in combination with the use of software options could not increase values of leaf area index (LAI) estimations. However, close correlation between LAI_{pca} and actual LAI indicated that the PCA could be used for measuring of leaf area development.

- Due to variations in cultivar and growth conditions, actual leaf area as well as the onset of leaf area development varied substantially between the vineyards monitored in this study. For the winter rainfall region development patterns of normalized leaf area index, however, tended to be fairly similar, irrespective of cultivar or growth conditions. Normalized leaf area index development of Sultanina vineyards in the warmer summer rainfall region showed extended leaf activity and growth during the post harvest period.

- Variation in normalized leaf area index development could be estimated by means of a third order polynomial equation using day of season as the independent variable and taking bud break as day one.

- Using cane mass to estimate maximum leaf area, which is needed for conversion of normalized leaf area to actual daily LAI values, would probably not be as accurate as using fresh leaf mass. However, using the latter parameter has practical limitations. Furthermore, it was found that horizontal canopies tended to produce more leaf area per unit cane mass in comparison to vertical canopies.

- Water required by the seasonal above-ground growth amounted to maximum values of about 7 millimetres. Water extracted daily and stored in the above-ground parts of the grapevine only amounted to fractions of a millimetre. Hence, in calculating daily water consumption, this water could be ignored.

- Mini-lysimeters proved to be accurate for measuring evaporation losses. Due to finite column length, evaporation could be underestimated if mini-lysimeters are used for periods longer than two weeks.

- Evaporation from unmulched, untilled soil could be estimated with acceptable accuracy by using the Boesten & Stroosnijder model. Since this model was initially developed for bare, fallow soils, some adaptions were necessary to account for canopy shading effects.

- Although β-values obtained in this study were higher compared to previous research, it was not sufficiently serious to have had a detrimental effect on the overall performance of the model.

- During stage two evaporation, evaporation losses from the soil (E_s) tended to be higher under a horizontal trellis in comparison to a vertical trellis. Under comparative conditions, rate of E_s differed between the six soil types used in this study.

- Mulching reduced evaporation losses significantly under relatively wet soil conditions. For most soils there were no difference between evaporation from unmulched soil and mulched soil ten days after irrigation. Cumulative E_s from mulched soil correlated linearly with cumulative ET_o for up to three weeks after irrigation. $\sum E_s$ generally amounted to 30 % of $\sum ET_o$.

- Verification studies, where simulated ET was compared to actual ET measured for eight vineyard situations, showed that the crop-specific model can predict ET satisfactorily.

- Viticultural inputs such as cane mass, plant spacing and canopy orientation can easily be obtained by growers. Reference crop evapotranspiration data for the nearest weather station can be obtained from a national meteorological data base.

8.3 PERSPECTIVE

This study offered the following perspective : Water consumption or irrigation requirements vary between vineyards. An understanding of the plant and soil factors influencing evapotranspiration is essential to develop improved irrigation management practices to optimize production and quality. An important approach to irrigation is modelling water consumption. This process is, however, complicated by variation in transpiration losses as well as evaporation losses from the soil surface. To account for these variations would require a vast number of input parameters. Obtaining these parameters would be time consuming and not always practical on a commercial scale. Calculating evapotranspiration by means of a model is dangerous if it is not verified by actual water consumption studies in the field and by practical experience. With this study, a start to evaluate the use of selected input parameters has been made. Although refinements will be necessary, verification studies have proved, that the concept to separate transpiration and evaporation and then use parameters such as leaf area per vine, canopy surface orientation, cane mass and reference crop evapotranspiration, to predict water consumption of individual vineyards can be considered as a first approach.

8.4 FUTURE RESEARCH

- The effects of increase in shading with increase in leaf layers, cultivar characteristics, locality and water stress should be investigated by further research to refine estimation of transpiration.

- One of the major shortcomings of the model is the uncertainty about the relation between leaf area and transpiration during the post harvest period.

- The incomplete list of known β-values will limit the application of the model. Hence, it is vital to determine this parameter for more soil types.

- Research should be aimed at establishing means to predict the variation in β-values for soils as well as different tillage practices applied in South African vineyards.

- Unsaturated hydraulic conductivity would probably be the best parameter to explain variation in evaporation behaviour among the different soil types and should be investigated by further research.

- The effects of mulch thickness, mulch material and loosening of the soil surface by tillage on evaporation losses should also be refined by further research.

- It must be realized that any model becomes more complicated as the number of inputs increase. Therefore, the objective of future research should be to find a balance between acceptable accuracy and the economy of the model.

- Since the model estimated water consumption satisfactorily, a computer program should be developed to facilitate the calculation of seasonal water consumption from long term average reference crop evapotranspiration for use in planning of water storage capacities and in irrigation system design. Furthermore, the computer program must also enable producers to predict real time water consumption on a daily base.